ASSESSING ECONOMIC IMPACTS OF GREENHOUSE GAS MITIGATION

SUMMARY OF A WORKSHOP

Derek Vollmer, Rapporteur

Board on Energy and Environmental Systems

Division on Engineering and Physical Sciences

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Preface

The workshop on Assessing Economic Impacts of Greenhouse Gas Mitigation was motivated by recognition of the need for improved analytical capabilities and tools for developing policies to address greenhouse gas mitigation and climate change. Various models and tools exist and are in use, but as climate science advances and new questions arise regarding the economic consequences of action (or inaction), there will be a need for analysis that can provide rich detail, communicate sector- and region-specific impacts, and reflect the myriad uncertainties embedded in technological change, nonlinear processes, and global involvement. This workshop represented an effort to engage leaders from the policy, economic, and analytical communities to help "define the frontier" and provide insight into the opportunities for enhancing existing capabilities to assess economic impacts.

This workshop summary follows the general issue areas discussed at the workshop. After a brief introduction, it summarizes the main themes from each panel and the resultant discussions. The workshop was open to the public, and thus the summary reflects the presentations of invited panelists as well as the issues raised by audience members. This summary does not include any consensus views of the participants or the planning committee, does not contain any conclusions or recommendations on the part of the National Research Council, and does not contain any advice to the government, nor does it represent a viewpoint of the National Academies or any of its constituent units. No priorities are implied by the order in which ideas are presented.

This workshop was organized by a planning committee of experts who played an integral role in developing an agenda, identifying speakers and participants, and moderating discussions during the workshop. I extend sincere thanks to Richard Newell, Marilyn Brown, Paul Joskow, and John Weyant for their contributions in scoping, developing, and carrying out this project. Panelists and audience members all contributed to a day and a half of stimulating discussion that this workshop summary strives to reflect clearly.

Jim Zucchetto and Peter Blair of the Division on Engineering and Physical Sciences provided valuable program direction for this project, for which I am grateful. Jonathan Yanger also deserves special recognition for his program support on this project.

This workshop would not have been possible without the financial support of its sponsors: the U.S. Department of Energy's Office of Policy and International Affairs, and the Alfred P. Sloan Foundation. Inja Paik and Bob Marlay of the Department of Energy provided useful input to the planning committee, which helped it to develop a workshop that was both timely and valuable to the various policy, economic, and analytic communities engaged in the many aspects of greenhouse gas mitigation.

This workshop summary has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the review process.

We wish to thank the following individuals for their review of this workshop summary: Jay Braitsch, U.S. Department of Energy; Jae Edmonds, Pacific Northwest National Laboratory; Mun Ho, Harvard University; Adele Morris, the Brookings Institution; and Richard Richels, Electric Power Research Institute.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the summary, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the author and the institution.

Derek Vollmer
Rapporteur

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1
Introduction

Many economic models exist to estimate the cost and effectiveness of different policies for reducing greenhouse gas (GHG) emissions. Some approaches incorporate rich technological detail, others emphasize the aggregate behavior of the economy and energy system, and some focus on impacts for specific sectors. Understandably, different approaches may be better positioned to provide particular types of information and may yield differing results, at times rendering decisions on future climate change emissions and research and development (R&D) policy difficult. Reliable estimates of the costs and benefits to the U.S. economy for various emissions reduction and adaptation strategies are critical to federal climate change R&D portfolio planning and investment decisions. At the request of the U.S. Department of Energy (DOE), the National Academies organized a workshop to consider these issues.

A planning committee was appointed by the National Research Council to organize the workshop and moderate discussions. Richard Newell (Duke University), Marilyn Brown (Georgia Institute of Technology), John Weyant (Stanford University) and Paul Joskow (Alfred P. Sloan Foundation) worked with National Academies staff to organize the two-day event in Washington, D.C. The workshop was structured to encourage discussion of key policy questions, modeling approaches, assumptions, and uncertainties, to help clarify some of the debate, identify opportunities for advancing the capacity for economic analysis of climate policies, and assist the U.S. Climate Change Technology Program (CCTP) in guiding future investments in the U.S. federal R&D portfolio.

As planning committee chair Richard Newell put it, the workshop comprised three dimensions: policy, analysis, and economics. Discussions along these dimensions were meant to lead to constructive identification of gaps and opportunities. The workshop focused on (1) policymakers' informational needs; (2) models and other analytic approaches to meet these needs; (3) important economic considerations, including equity and discounting; and (4) opportunities to enhance analytical capabilities and better inform policy.

Robert Marlay, deputy director of the CCTP, explained that both the DOE and the broader CCTP are interested in building analytical capacity to help understand and inform complex decisionmaking around climate change policy. The CCTP covers 13 agencies engaged in facets of climate change, all interested in this discussion on how to assess the economic impacts of various policies, what the limitations are of these assessments, and what economics more broadly can tell us about how effective policies might be designed. He noted that, from a policymaker's point of view, recent economic analyses of the Lieberman-Warner bill, for example, have yielded results that vary by more than an order of magnitude, which is confusing to those not familiar with the process of modeling for these sorts of bills. Several modelers and analysts responded to this point and explained that these apparently disparate results, when controlled for certain variables, yield a tighter distribution of results than what is conveyed to the lay person. Thus, a theme that emerged early in the workshop is that modelers need to give more careful consideration to how their different results compare, and how that is communicated to the public.

Marlay also remarked that the questions being asked of policymakers are also requiring information at increasing levels of detail, going far beyond simple macroeconomic impacts. Specifically, such questions indicate interest in modeling results for specific industries or economic sectors. Legislators are seeking information on impacts at a state or even district level, and also among different income levels within a population. Still others are interested in impacts across countries, and the implications for material and trade flows. Finally, he noted that policymakers are interested in the degree of confidence placed on the estimates they are seeing.

The DOE recently completed a survey of existing analytic tools, focusing specifically on the technology and economic models in current use both domestically and internationally. Marlay remarked that the models are providing insight into potential costs but that much less information was being generated about the various courses of action and potential benefits. Specifically—and this point is important to policymakers—there has been less consideration of the tradeoffs among mitigation, adaptation, and inaction. Participants recognized that an array of tools will be needed to develop climate change policy, and were challenged throughout the workshop to identify potential gaps and areas for improvement within the current suite of models and analytic tools. Given the anticipation that a new U.S. administration will be calling for information to help make decisions on legislation, inform international negotiations, and design multibillion dollar R&D programs, this workshop was intended to identify some of the key challenges posed for improving this information, specifically with regard to assessing economic impacts. Marlay informed participants that the CCTP intends to form partnerships with strong analytical elements of each participating agency within the CCTP, and that the work would not or could not be left to just one agency. The CCTP will then make additional investments to strengthen these existing tools, and so he expressed hope that this workshop would help define the frontier of climate economics analysis and push it forward. The following four chapters summarize what transpired during the four panel discussions and highlight their major themes.

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Policymakers' Informational Needs

To orient the workshop's discussions toward meeting the needs of the policy community, the initial session was structured to outline the pressing issues that policymakers hope can be informed by analysis. Panelists identified the range of specific informational needs expressed and questions asked or likely to be asked in the future by policymakers regarding the design, impacts, and outcomes of climate change policies and related energy policies. Panelists included Robert Shackleton, Congressional Budget Office (CBO); Howard Gruenspecht, U.S. Energy Information Administration (EIA); Francisco de la Chesnaye, Electric Power Research Institute (EPRI); Nat Keohane, Environmental Defense Fund; and Tim Profeta, Duke University.

Bob Shackleton opened the discussion by first noting that CBO pays a lot of attention to what the research community is doing, and how this activity affects policy formation, and he made the point that it was science that initiated the climate policy process decades ago. He noted, as did several other participants, that research provided valuable insights into the consequences of freely allocating carbon allowances, for example, which led policymakers to consider auctions for carbon. Research has also led to an evolution in thinking about the flexibility of specific policies (i.e., in general, greater flexibility seems to yield greater economic efficiency). This chapter summarizes the subsequent discussion, highlighting some of the main themes that emerged, including communicating results; representing behavior and technology adoption; suboptimal scenarios and quantitative targets; modeling policy interactions; and impacts, distribution, and equity considerations.

Communicating with Policymakers

Howard Gruenspecht remarked that the bandwidth for communication with policymakers is narrow, and thus it is useful for analysts to focus on key insights that are not dependent on particular parameters unique to an analytical framework. Like the research Bob Shackleton mentioned, which influenced policymakers' consideration of flexible approaches (Richels et al., 1996), Gruenspecht said that these kinds of insights are more valuable than numbers that come out of one particular framework. He also emphasized that policymakers' needs and wants should be differentiated and that the onus is on analysts to strike a balance between delivering what is asked of them, and instructing policymakers about the types of questions they should be asking.

Addressing the issue Bob Marlay raised about confusing analyses of the Lieberman-Warner bill, Francisco de la Chesnaye stated that, to those familiar with the models, the disparities were largely and easily explained by differences in certain assumptions.[1] Nevertheless, he stressed that analysts must do a better job of comparing analyses and communicating the insights from these comparisons. As an example, he presented a figure (Figure 1, *top*) that displayed several analyses of the Lieberman-Warner bill, followed by a figure (Figure 1, *bottom*) in which the analyses were all controlled for specific constraints. Figure 1 (*bottom*) shows a much tighter distribution, which leads to a more useful bounding of estimates

[1] A distinction should be made between baseline assumptions (e.g., population growth), which are relatively uniform among the models, and assumptions about substitution elasticities, market clearing, foresight, and other issues that largely determine the effects of a given policy.

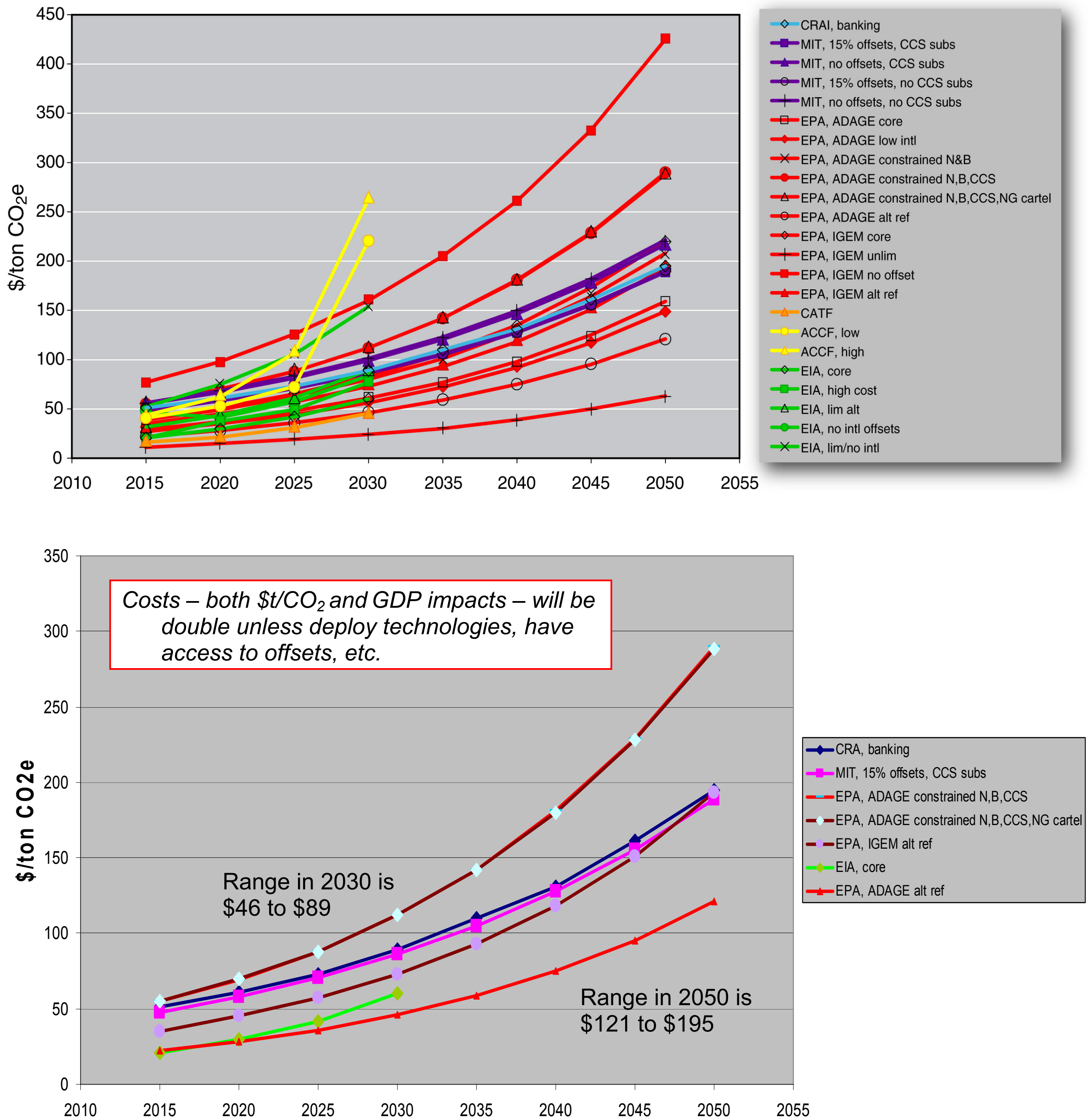

FIGURE 1. *Top:* Estimates of allowance costs of Lieberman-Warner bill from various analyses. *Bottom:* Screened marginal costs bill, highlighting the importance of modeling assumptions. NOTE: Results controlled for specified constraints on technology, assumptions on offsets, different reference cases, and bill interpretation. SOURCE: EPRI, 2008. Reprinted with permission of EPRI.

on factors like the range of costs per ton of CO_2. He noted that making these sorts of comparisons will require more cooperation among agencies and institutions, but that it could be done and would be of great value.

Nat Keohane drew a distinction between analyses of specific bills, and what he called policy experiments whereby modelers manipulate aspects of a proposed bill in an attempt to demonstrate, for example, the effects of introducing higher CAFE standards. These experiments may increase confusion and are also not particularly useful, given that existing and proposed bills cannot be modified so easily.

He also emphasized, as did other participants, that analyses should be transparent to the lay reader. However, participants did not explore what was meant by "transparent" or how transparency might be accomplished.

John Conti of EIA responded that in EIA's case, its model is quite transparent with hundreds of pages of documentation easily accessible, but this does not mean that a lay reader would understand it. Keohane suggested that analysts be prepared to be able to explain key assumptions to lay readers like congressional staff. He noted that Stanford University's Energy Modeling Forum (EMF) exercises, which engage many from the analytical community, are valuable but are still not transparent to non-analysts, or as he later put it, "The mechanics understand what is going on under the hood, and so the next step is to educate the driver." Tim Profeta suggested that modelers consider designing sensitivities (e.g., discount rates) and certain assumptions with more stakeholders at the table, as a way to make them more transparent. Adele Morris of the Brookings Institution suggested that the media and broader public should be made more aware of these underlying assumptions as well, and she offered the example of policymakers citing the benefits to be gained from a stringent scenario and the costs arising from a lax scenario, which is of course misleading.

Finally, Peter Evans of GE pointed out that although several corporations have developed their own ways to analyze and plan for climate change impacts, they are also avid consumers of formal model outputs. An important consideration for modelers, particularly when they are thinking about reporting on outputs, is thus that in addition to the policy community, the business community is quite interested in learning about analytical work on designing models to estimate economic impacts.

Representing Behavior and Technology Adoption

Decisionmaker behavior and its representation in models was a subject of discussion throughout the workshop. Howard Gruenspecht raised several related issues and stressed that in general, analysts need to focus more on behavior. He cautioned that simply taking underlying preferences as given was likely not a solid assumption, and that there had been too much attention to cost engineering and not enough attention to the behavior embedded in modeling assumptions. Other participants echoed this notion that economists have focused on costs whereas policymakers are perhaps more interested in feasibility. In other words, policymakers want to know how quickly energy efficiency would have to improve, and with what degree of certainty they might expect to see that happen.

Some models also assume the adoption of technologies that may not be universally accepted, and this has major ramifications in many of the modeling results . As has been the case with nuclear power in the United States, community and public acceptance in general will have an influence on the siting and construction of many technologies that models assume will be adopted based on cost alone. Several participants raised questions about how nuclear power and carbon capture and sequestration (CCS) were handled in models, because these two technologies have a large influence on the costs of programs but are not certain to be widely accepted. One suggestion was that analysts should be able to separate these types of technologies out and communicate the results of not using them versus using them (e.g., estimate costs of 3 percent of GDP without such technologies, and 1.5 percent if adopted). Such reporting of results could help bound expectations of costs, as well as signal to policymakers that they may need to expend additional efforts to generate support for or reduce opposition to technologies that are otherwise cost-effective. In this regard, Peter Evans of GE noted that there appears to be a need for some sort of "grand bargain" around coal, given its importance in economic projections, and wondered how modeling results might influence public campaigns or other ways to shape national or even international interest. Dallas Burtraw of Resources for the Future (RFF) seconded this idea, and Kerry King of the University of Texas remarked that his research team is beginning to conduct survey sampling in Texas to understand the level of community acceptance of CCS, as Texas is likely to be a test bed for the new technology in the coming years.

Suboptimal Scenarios and Quantitative Targets

Bob Shackleton described what he called the "unimportance of a quantitative target" with regard to climate policy analyses—there are so many uncertainties in terms of program implementation and climate response, that even if a specific target is achieved, such as stabilizing CO_2 concentration, there is always a possibility that costs will greatly exceed what was projected, or that temperature change will be higher or lower than expected. He commented that analyses have often focused on quantitative targets and first-best scenarios, but increasingly decisionmakers are requesting suboptimal (i.e., realistic) scenarios, and more attention needs to be paid to how researchers communicate the uncertainty of their results (e.g., by bounding estimates). He further pointed out that many projections are based on concerted global action, but individual countries, particularly the large energy consumers, can substantially shift potential temperature outcomes, and thus analysts ought to pay more attention to communicating how these individual actions can shift the outcome.

Howard Gruenspecht agreed that there has been too much emphasis on first best scenarios, and he emphasized, as did several subsequent participants, that policymakers are interested in the *n*th best scenario, not only the first or second. As noted earlier, he drew a distinction between policymakers' interests (their "wants") and their needs, and he encouraged economic analysts to explain the limits of existing analytical tools, but also to make efforts in their own analyses to go beyond ideal scenarios. Gruenspecht argued that analyses generally took a cost engineering approach, but like the question of technology acceptance, policymakers are just as interested in what might be feasible or expedient, even if it is not the most economically efficient. John Weyant also urged analysts to keep in mind that the models provide insights, not numbers—policymakers have sometimes had a tendency to give modelers a number, e.g., 2 percent of GDP, and then ask modelers to "fill in the rest," but this may not be feasible or desirable. As an example, he noted that one analysis of California's bill to regulate GHGs (AB32) concluded that a 100 percent regulatory approach could yield the same results as a cap-and-trade program (in terms of GDP), but this sort of analysis left out two of the most important benefits of a cap-and-trade approach—its ability to handle uncertainty and its flexibility in handling heterogeneous costs among sectors.

Modeling Policy Interactions

Bob Shackleton pointed out that complicated interactions will inevitably occur between climate policies and policies developed to address a variety of other issues. This reality signals a need to analyze complementary measures, especially in the transportation sector (e.g., a low-carbon fuel standard). He urged more attention to understanding how policies interact, because the reality is that a suite of policies and approaches will be utilized. He noted that some analysts had begun to consider interactions among price floors, price ceilings, and banking/borrowing credits (e.g., Murray et al., 2008), but that more work needs to be done in this area. He also reminded participants that policies would not be static and would be revised in light of new information, further underscoring the importance of analyzing their interactions.

Participants identified several gaps between what policymakers were asking and what analysts were considering with regard to policy interactions. Nat Keohane categorized these as policy gaps and methodological gaps. Policy gaps include complementary measures (e.g., a low-carbon fuel standard), trade measures, and revenue recycling. Methodological gaps include price volatility or cost containment, energy efficiency measures as captured in models, and baselines for renewables, especially in the electricity sector. Several other participants suggested that price volatility is an important concern among policymakers, but it is difficult to capture since models tend to predict a particular price path, which may not be realistic. There was also discussion of how energy efficiency is represented in models. Economists are not necessarily as optimistic as engineers about energy efficiency opportunities (e.g., Paul et al., 2008), and Howard Gruenspecht pointed out that many efficiency improvements are assumed in the models, thus there is a danger of double counting. This factor must be teased out further so as to provide insights to policymakers about how policy can most effectively help drive improvements in energy efficiency.

Tim Profeta raised the issue of state programs that are already underway ahead of federal government action—these will inevitably interact and will not necessarily be preempted by a federal program. Therefore, he urged more consideration of how state programs would interact with a uniform national effort—what are the potential efficiencies or inefficiencies of a patchwork approach? He also pointed out, as did subsequent participants, that transportation is being handled differently than other sectors. In some analyses, costs to electric utilities increase if transportation is included in a cap-and-trade program. Therefore, more work is needed to understand the impacts of alternative mechanisms to handle transportation, or to model the effects of incorporating the transportation sector at a later date. Transportation may also be subject to complementary measures such as a vehicle miles traveled (VMT) reduction program, and so analyses must consider potential complementarities.

Trade was another issue brought up by several participants. On the question of energy-intensive imports, Bob Shackleton noted that accounting for these will be one of the most important and persistent questions that must be addressed. Francisco de la Chesnaye urged more forward thinking on international linkages, such as how a U.S. domestic system might link to the international community, especially if a European program would not accept a safety valve (i.e. a price ceiling) for a cap and trade program. Tom Kram also noted that his colleagues at the Netherlands Environmental Assessment Agency recently released a study examining effects of border trade—this study assumes that the EU would proceed ambitiously with mitigation programs while the rest of the world lags (den Elzen et al., 2008).

Impacts—Distribution and Equity

Panelists and participants emphasized that policymakers are more interested in *relative outcomes* than in absolute outcomes in terms of GDP. Regional impacts are often more important, from a policymaker perspective, than an aggregated impact, and globally, countries might be more concerned with impacts vis-à-vis a neighbor or competitor and thus with relative rather than absolute gains. Bob Shackleton pointed out that this sort of information may not be as relevant to estimating temperature outcomes but is vital to getting policies in place. He also noted that there is an interest in better calculations of benefits, including damages averted—policymakers want a realistic understanding of what the likely outcomes are of various policies, or what the relative outcomes are. This is critical to mitigation policy development, policy stringency, and timing.

Understanding the distribution of costs is vital to policymakers. Shackleton pointed out that policymakers are interested in more detailed analyses on impacts by sector and industry, impacts at a state level, changes in the job market, impacts at various income levels, and international material and trade flows—in short, policymakers care more about equity and distribution than efficiency. Policymakers are particularly concerned with burdens that might be imposed on low-income households, and how existing policy frameworks might be utilized to offset some of these impacts. Nat Keohane agreed that distribution and equity are primary concerns because impacts are regional as much as they are partisan. He noted, as did many participants, that not enough models can provide estimates of regional impacts. He further pointed out that equilibrium models are often based on full employment, but this assumption is not realistic, and policymakers are very concerned about impacts on jobs.

Keohane also questioned how well models were able to identify “winners and losers” among industries. He stated that information on allocations and industrial performance is likely to need updating. Dimitri Zenghelis agreed that policymakers would like clarity about the amount of risk faced by energy-intensive industries in particular, and noted that a recent report by the World Resources Institute and the Peterson Institute for International Economics (Houser et al., 2008) suggests that these risks might be exaggerated in the absence of firm analysis.

3
Models and Analytical Approaches

Following the discussion of policymakers' or end-users' informational needs, the next panel provided a brief overview of several models and analytic approaches currently available. Not all models were represented (notably MARKAL, the technology-rich DOE-supported model), but collectively the panelists offered a reasonable glimpse of existing analytical capabilities. Panelists were John Conti, EIA; Richard Goettle, Northeastern University; Leon Clarke, Pacific Northwest National Laboratory; John Reilly, Massachusetts Institute of Technology; Dallas Burtraw, Resources for the Future (RFF); Jean-Marc Burniaux, Organisation for Economic Co-operation and Development (OECD); Tom Kram, Netherlands Environmental Assessment Agency (MNP); and Peter Evans, GE.

Rather than focusing on specific modeling results, panelists presented the capabilities and high-level structure of these approaches, advantages and disadvantages relative to other approaches, how decisionmakers are using these tools, and whether and how the approaches incorporate uncertainty. At the outset, several speakers noted that existing models are complements to one another—they each have unique strengths and are not interchangeable. Thus, discussions focused on perceived informational gaps within the collective community and any opportunities to enhance existing capability (e.g., through improved data). This chapter summarizes the key features of the analytical approaches presented at the workshop and the major themes addressed by presenters and participants. Specifically, discussions focused on existing models, their data limitations, and how the models characterize technologies, policy effects, major sources of uncertainty, behavior, and systems interactions.

Existing Models and Analytical Approaches

National Energy Modeling System

The National Energy Modeling System (NEMS), managed by EIA, is the direct result of a National Research Council study that provided recommendations to EIA on improving its modeling capability to better inform DOE's national energy strategy (NRC, 1992). A partial equilibrium model of the U.S. energy economy, NEMS provides projections for imports, exports, conversion processes, and prices. One of its primary outputs, the Annual Energy Outlook, serves as a baseline for several other models. NEMS is linked to the Global Insight macroeconomic model and relies on EPA's estimates for non-CO_2 gases. Modules represent specific sectors (supply, conversion, end use). Depending on end-use sector, NEMS may utilize a number of different methodology paradigms, including adaptive expectations, myopic expectations, and perfect foresight. Outputs are regionally specific, roughly following the 10 U.S. census regions, and exhibit rich technological detail that is econometrically estimated and dependent on exhibited historical behavior.

Intertemporal General Equilibrium Model

The Intertemporal General Equilibrium Model (IGEM) was developed and is managed by Dale Jorgenson and Associates and is an intermediate-term (20-50 year) model of the growth and structure of the U.S. economy. It represents 35 producing sectors and utilizes three sources of primary inputs: capital, labor, and non-competing imports. Unlike dynamically recursive or myopic models, IGEM has perfect foresight.[1] Like other CGE models, IGEM's outcomes are largely influenced by household-level decisions on labor, consumption, and leisure. It is sometimes criticized for assuming perfectly mobile capital and labor, but its substitution effects are econometrically estimated based on market behavior observed over the past 50 years. IGEM's reliance on observed behavior and empirical data makes it rich in detail and substitution possibilities; there are more than 12,000 substitution parameters, and so measurable variance-covariance matrices (which IGEM has) are increasingly important to help account for imprecision in the parameter estimates. This is a potential advantage of the econometric approach, since it can potentially put bounds on uncertainty; IGEM's operators are just beginning to work in that direction, though such an effort requires significant time and resources.

MiniCAM

MiniCAM is an integrated assessment model (IAM) operated by Pacific Northwest National Laboratory. Like other IAMs, MiniCAM is a complete model in the sense that it models the entire globe and includes not only human and economic systems, but also their interactions with physical systems. It models out to the end of the 21st century; although it captures at a high level all of the interactions possible among agriculture, land use, climate, energy, and other systems, it is not able to provide regionally specific or short-term outcomes. MiniCAM operators also engage in integrated assessment research, in which they work with and incorporate detailed systems models (e.g., for ecosystems or carbon capture and storage) that then feed back into the IAM. These nested models can also help scale down impacts to a more regional level. MiniCAM's focus is on energy, agriculture, and land use markets in 14 world regions, and it is fairly detailed from a technology standpoint. In this regard, much of its research has focused on drawing insights about the relative importance of different energy technologies.

ADAGE

ADAGE, a dynamic CGE model with foresight, is operated by RTI. Its coverage is both international and regional within the United States, and so it can be used to model regional energy production as well as international policies and their impacts on trade flows. It is flexible in that it can parse out a sector such as agriculture into its various components for further analysis. EPA is currently working with ADAGE operators to examine how climate change might affect sectors ranging from agriculture to human health.

EPPA

EPPA is a CGE model that is part of a broader integrated system operated by MIT. It represents and balances primary factors of production, the goods and services produced, and the income accrued and spent by households. Recently, operators have made additions to EPPA to account for perceived weaknesses or shortcomings of the model. Specifically, they have added household transportation with a variety of vehicle and fuel types, a recreation system that examines competition in land use demand between recreation and biofuels, and a health services sector that reflects damage caused by air pollution.

ENV-Linkages

The OECD utilizes a CGE model with world coverage (22 sectors and 12 regions) and it covers 50 years with recursive dynamics. OECD's clients, its member countries, have tended to focus on medium-term (as opposed to longer-term) outcomes, and are interested in the policy responses to issues such as carbon leakage or trade and competitiveness. More recently, operators have begun work on modeling "hybrid" approaches that include some level of countrywide reductions, coupled with sectoral agreements for certain energy-intensive industries, as well as existing energy subsidies that affect

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[1] Perfect foresight does not imply that decisionmakers will precisely know the future, but it does assume that they are fully aware of all contingencies and the probabilities associated with these contingencies.

mitigation cost. They have also started to analyze implications for worldwide emissions trading. In particular, they are modeling scenarios for varying carbon allocation rules.

IMAGE

The Netherlands Environmental Assessment Agency (MNP) operates a global coverage model similar to the MIT-EPPA model. IMAGE represents 26 regions at a resolution of 0.5 degree by 0.5 degree. It integrates energy, land use, food security, climate, and air quality in one framework and is used to analyze long-term (2050-2100) issues. From a technology perspective, IMAGE is relatively aggregated, though it does include advanced options such as biomass power plants with CCS. Climate change feedback is represented and affects land use and energy demand. The MNP is also now working to disaggregate regional data, with the hope of shedding some light on the positions of different countries—some countries will likely experience damages that exceed their expected GHG mitigation costs—and this information may be useful in formulating a more equitable global response to climate change.

Haiku

Resources for the Future (RFF) models the U.S. electric utility sector using the Haiku model. It solves for the electricity sector in 21 U.S. regions, and unlike some other electricity market models, it explicitly accounts for the structure of cost recovery in different regions of the country (whether it is market-based or based on regulation of the cost of service). It also includes a fuel price response to demand. Dallas Burtraw noted that, although the Haiku model may not handle uncertainty any better than other models, RFF is using the Delta method when looking at safety valves, and at the influence of a price cap and price floor on variability in allowance price transactions. RFF has also linked to an investor behavior model and is using stochastic dynamic optimization to analyze how those who invest in CCS would respond to equilibrium conditions, given the uncertainty in that market.

Scenario Planning

Within GE, analysts are using scenario planning to help the business units understand the social, economic, and political ramifications of climate change. Their primary interest is in technology change, both its rate of deployment and its effects on factors like energy efficiency. Evans provided three reasons that GE takes this approach: to deal with rapid change and uncertainty in national and international energy markets; to improve long-term technology investment decisionmaking within the company; and to enhance organizational learning. They use three scenario frameworks: Asia Rising, Changing Climates, and Global Rifts. Each scenario provides a unique framework for thinking about how the future could unfold and the technology pathways that might result.

Data Sources and Limitations

Baseline assumptions are the biggest source of uncertainty for several of the models. Assumptions about world oil prices, technological progress, or population growth can have important implications, particularly beyond 2030. These sorts of assumptions determine the "business as usual" scenario. In the shorter-term, even the changes in EIA's Annual Energy Outlook 2008 (notably the Energy Independence and Security Act) affect the baseline for many models. John Conti noted that Congress would like NEMS to model at the state or district level, but sufficient data does not exist. End-use data and consumption surveys would aid the EIA in providing a richer level of detail, and from his perspective, industrial sector data is most in need of improvement. DOE has programs that extend NEMS results out to 2050, but it becomes difficult to fill in the detailed data assumptions that would drive the model beyond its 25-year timeframe. John Reilly stated that MIT is developing a U.S. regional model that would eventually support a state-level modeling system, but access to regional detail (especially plant-level) will be critical.

IGEM, like other CGE models, is largely empirically based. Social accounting matrices come from the National Income of Product Accounts (U.S. Bureau of Economic Analysis). Many models also draw from the Global Trade Analysis Project (GTAP), a database containing bilateral trade information for more than 40 countries and 50 sectors. IGEM's representations of price- and policy-induced technical change are based on observed behavior over 40-50 years, though its managers recognize that past performance is not necessarily indicative of what will happen in the future. IGEM does not represent feedback effects, and so "shocking the system" will not change the parameters themselves.

Technology Characterization

Marilyn Brown noted that the multiplicity of technology options available can sometimes be a deterrent to action—policymakers want to know what their *best* option is. Therefore, she wondered how models might be able to offer additional insight into the role of specific technologies, such as different low-carbon fuels, or tradeoffs between all-electric and plug-in hybrid cars. This level of technological detail often confines the timeframe for estimates. For technology-rich models like NEMS, assumptions about specific technologies that go beyond 25 years or so are both difficult to make and highly uncertain. MiniCAM attempts to draw out insights over a longer timeframe (100 years), but Leon Clarke cautioned that technology assumptions are even more influential in its model outcomes. In general, it is more difficult to get technology richness in the more top-down models. ADAGE and other CGE models can try to isolate the electricity sector and include specific technologies directly in the model, or, as EPA has done, it can link results from other modeling frameworks.

Jay Braitsch of DOE noted that technology progress is among the most important of the assumptions made by the DOE in its modeling efforts. IMAGE and several other models use a simple learning-by-doing approach to represent technology learning. In the case of IMAGE, it is affected by resource depletion (including competition for biomass), and in the case of renewable resources, it is also influenced by distance from human settlements. As noted in the discussion on policymakers' information needs, technology acceptance is also an important consideration that is not always being reflected in models as another uncertainty factor. Dallas Burtraw recalled that in the 1970s, few analysts would have forecast that the nuclear power industry would have such difficulty in siting and building new plants; a similar situation is playing out for many coal plants in the United States, and so the business as usual reference case may no longer apply.

Representing Policy Effects

Detailed and complex legislation must be characterized to fit into the models, and while it is not generally a problem to represent the instruments, there is a great deal of uncertainty surrounding what these policies would actually accomplish. Many CGE models capture rich substitution possibilities, based on observed behavior. However, for all models, it is less clear that historical behavior accurately represents the choices consumers would make today or in the future. Forward-looking models, which optimize over time, tend to yield lower macroeconomic costs than do myopic dynamic models, because actors know what will happen in the future and can plan accordingly. The models can use behavioral elasticities to reflect, for example, slow household response to price changes, but capturing explicit distortions is difficult. These substitution elasticities have an important bearing on costs, in both static and dynamic models. John Reilly also pointed out that credit systems like the Clean Development Mechanism (CDM) are not nearly as efficient as a cap-and-trade program, but the credit supply curves are generally based on some sort of cap.

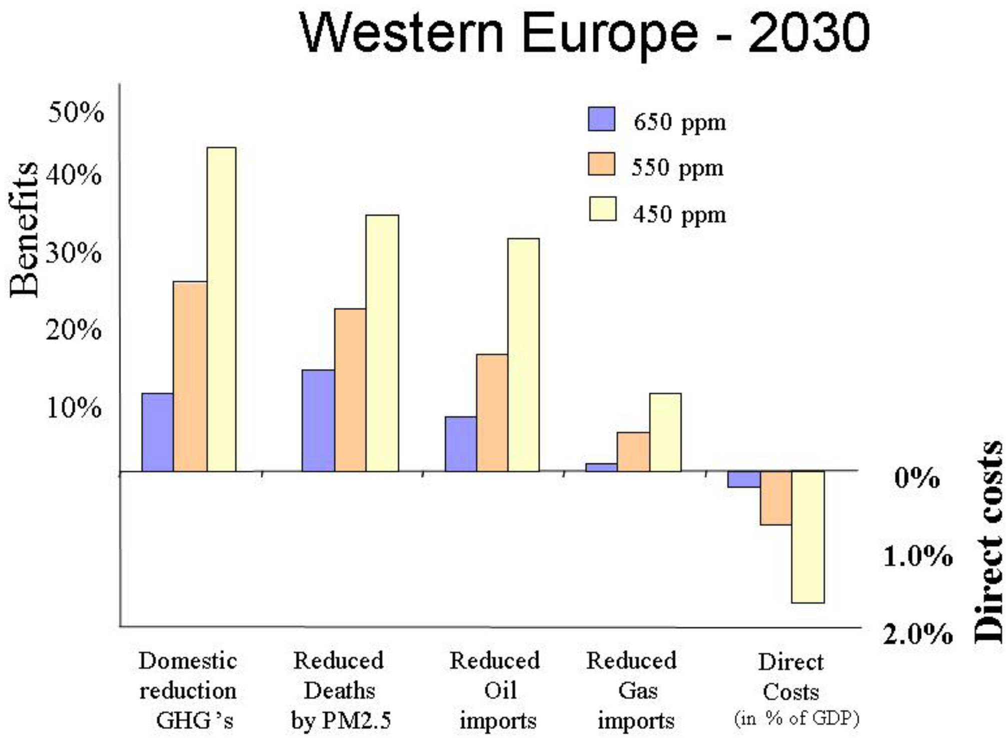

FIGURE 2. Relationships among energy security, air quality, and climate goals, as modeled under different scenarios for Western Europe. SOURCE: Tom Kram, Netherlands Environmental Assessment Agency, presentation given at the Workshop on Assessing Economic Impacts of Greenhouse Gas Mitigation, National Academies, Washington, D.C., October 2-3, 2008.

NEMS is able to model many policies currently under consideration because it has a fairly detailed transportation module embedded in the system—as workshop participants noted, the transportation sector is often treated separately, and thus models must account for, among other things, specific fuel economy requirements. NEMS's modularity also allows its managers to work on particular modules as specific programs (e.g., CAFE standards) are modified. IGEM has a rich and detailed tax structure, which allows it to examine a variety of revenue recycling schemes and alternatives to a particular climate policy.

Tom Kram noted that in the Netherlands, MNP is receiving questions about economic impacts on low income groups; the Netherlands Economic Bureau no longer has a detailed sectoral model that might help analyze this, and so currently MNP is unable to assess specific impacts. He also noted that clients are interested in understanding the side benefits of taking action to reduce emissions, and that is represented in terms of import reductions and human health benefits as compared to direct costs (Figure 2).

When considering targeted use for allowance values, Dallas Burtraw suggested that much more work is needed to examine incentives in the second-best construct. There will be administrative costs, free riders, and missed opportunities in efficiency programs, and he wondered whether or not there are insights into effective mechanism design to incentivize investment in efficiency. On the role of state and local governments, he noted that most analyses are not sufficiently considering the impact of these subnational policies and practices. Issues ranging from local land use ordinances to the Regional Greenhouse Gas Initiative (RGGI) will undoubtedly influence the kinds of action taken on the ground. He also noted that incidence analysis is important, and that his model finds, for example, that the way in which allowance values are recycled largely determines who bears the burden of the program. In other words, few existing models can incorporate subnational policies or analyze the incidence of different cap-and-trade program designs, but both are important for understanding federal options.

Identifying and Quantifying Uncertainty

Sensitivity analyses are useful to identify key areas of uncertainty within the modeling community. They are especially important for the largest models, to examine critical issues in some isolation, such as the Env-Linkages model did recently to look at carbon leakages. Janet Peace of the Pew Center on Global Climate Change did note that sensitivities tend to be conservative and do not often consider efficiency improvements or technology development occurring more rapidly than one would ordinarily expect. National models like NEMS require more sensitivity to international experiments. A more comprehensive analysis, the Monte Carlo simulation, is difficult for the large and complex models, even with low-cost computer time. John Reilly noted that MIT recently completed a Monte Carlo analysis of the EPPA model (Webster et al., forthcoming). IGEM is experimenting with the Delta method to exploit the standard errors in parameters and the standard error in, for example, the estimated energy input demand function, to try and create confidence intervals around the outcomes it produces—an approach that might be applicable to other large-scale models.

Representing Behavior

Building on discussions from the previous panel, several workshop participants remarked on the importance of behavior and how it is represented in the various models. Marilyn Brown pointed out that as social preferences evolve, there may be generational differences that are not currently captured by modeling, such as a preference for walkable (i.e., not car-dependent) communities, or a preference for locally produced foods. Tom Kram noted that the Netherlands Environmental Assessment Agency has embarked on a study to examine the relevance of dietary preferences, specifically moving from an animal-based diet to a more vegetarian-based diet. Many participants remarked that absence of a capability for modeling evolving preferences is currently a major limitation of most available analytical tools. Richard Goettle wondered whether the functional forms in the models actually represent the right way to look at the world. Models focus on things like maximizing utility, but that may not reflect real-world household decisionmaking.

John Conti noted that NEMS tries to incorporate behavior in its estimates, by going beyond least-cost modules. Dallas Burtraw stated that the demand side of the electricity equation is where the Haiku model faces its biggest challenges now. One area is the role for efficiency, and attempts have been made to address this by looking for opportunities on a broad national scale, and combining those with incentive-based programs to promote energy efficiency. He emphasized that consumers consume electricity *services*, not kilowatt-hours, so how does incentive-driven behavior affect outcomes? Resources for the Future is now trying to model the effects of time-of-day pricing in the electricity sector.

Peter Evans pointed out that international relations research has suggested that as countries interact, they may not act “rationally” in the economic sense by pursuing absolute gains, and instead might be concerned with relative gains. Several other participants noted that analyses are only beginning to take this in to account. On a similar point, Tom Kram explained that regional differences among countries in terms of preferences can be significant, but these are not captured in global models.

Systems Interactions

One important insight that IAMs provide in particular is human-Earth systems interactions. While this linkage makes detailed regional or inter-temporal results difficult, it does offer several advantages, particularly for examining international impacts. For example, if countries delay or stagger mitigation measures, this has important ramifications for global crop production. EPPA is also modeling interactions among land-use change, terrestrial carbon emissions, and related factors, which is critical in analyzing interactions between mitigation and adaptation: EPPA and other IAMs reflect not only economic impacts, but also longer-term impacts on natural systems, which in turn help estimate potential damage, or impacts avoided (Figure 3). Dallas Burtraw pointed out that there is a need for a better understanding and incorporation of temperature changes in models' baseline scenarios, to analyze the effects on changes in electricity demand. Beyond the interactions of physical or natural systems, Peter Evans remarked that there is a need for more information on and understanding of the relationships between governments and markets. Evans discussed what he called "green industrial policy" through which governments are beginning to intervene in the market, in the name of climate change, and this will have important ramifications going forward.

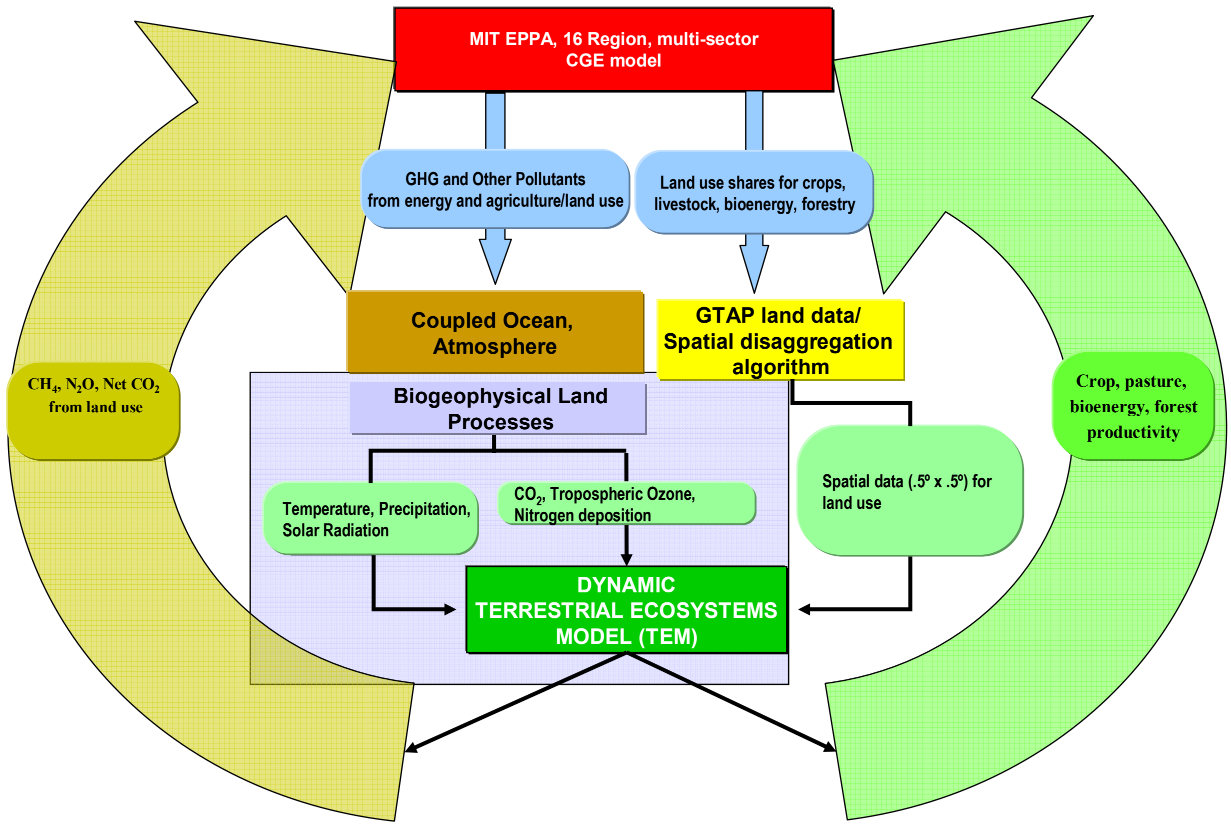

FIGURE 3. Interaction of mitigation and adaptation through land/biofuels. SOURCE: John Reilly, Massachusetts Institute of Technology, presentation given at the Workshop on Assessing Economic Impacts of Greenhouse Gas Mitigation, National Academies, Washington, D.C., October 2-3, 2008.

4
Economic Considerations

This session explored the state of the economics of climate change, and the role of economic analyses in climate policy decisionmaking. Panelists discussed key modeling assumptions, advantages, and limitations, potential impacts on the U.S. and world economies, approaches to estimating benefits and costs of mitigation, and the intertemporal and distributional equity issues associated with climate change and mitigation. Panelists included William Nordhaus, Yale University; John Weyant, Stanford University; Joel Smith, Stratus Consulting, Inc.; Richard Bradley, International Energy Agency; Dimitri Zenghelis, London School of Economics; and William Cline, Peterson Institute for International Economics. Nordhaus opened the discussions by reminding participants of the scientific data on global CO_2 concentrations and mean temperature which initiated the debate on climate change decades ago. He suggested that there is a serious lack of attention to time series analysis that could inform modeling efforts going forward. Such data will be extremely valuable in identifying the temperature sensitivity coefficient. This chapter summarizes the major themes of the panel discussion.

Assessing the Value of Impacts and Damage Averted

Joel Smith attributes weaknesses in the impacts literature to "looking for car keys under the lamp post"; that is, estimates of impacts have been based on a few modeling exercises and their outputs, generally focused on a narrow range of changes in climate (2-4°C), out to about 2100. However, climate change will not stop at 2100, nor is it confined to such a narrow range. The Stern Review (Stern, 2007) did attempt to begin calculating consequences of greater warming, and the IPCC report (IPCC, 2007) stressed the notion of risk management. Estimates should not focus only on the most likely outcomes, because some low-probability outcomes could be very important and consequential. On a related point, estimates of impacts have tended to focus on average changes, giving less attention to changes in variability, be it an extreme event or year-to-year variability. Ed Rubin echoed the notion that the ability to model and quantify climate change impacts is still weak relative to the ability to quantify costs. Improved modeling will require persistent, creative, and certainly interdisciplinary work. Also required will be more attention to how these impacts are valued.

Smith also remarked that there has not been enough attention to what the models leave out. As an example, impacts of sea-level rise have been estimated for some adaptation measures, including building sea walls, and assessing the value of inundated land. However, the impacts on human welfare when populations are adversely affected are not well known. In the agricultural sector, impacts are estimated for changes in production, consumer surplus, producer surplus, and net welfare, but adaptation appears to be cost-free even though that will certainly not be the case. The same can be said when considering water resources—changes in welfare accounted for in modeling include availability and quality, but not adaptation costs. Building reservoirs, controlling (or recovering from) flooding, and maintaining water quality could all entail significant costs not currently well captured. Smith also stated that more research is needed on climate change's impacts on air quality: increases in criteria air pollutants, for example, could lead to damage that would dwarf the damage attributed to heat stress, as well as other kinds of damage that models do consider. Estimates of the global effects of climate change on energy demand could also use revising and updating. Finally, he pointed out that new problems are likely to emerge, such as the erosion of shoreline occurring in Alaska now as a result of sea ice receding. These impacts were not foreseen but ought to be accounted for.

Bill Nordhaus commented that the IPCC report did not make an effort to synthesize what is known about impacts, which would have been helpful to modelers trying to represent impacts. What has not changed since early reports from the 1980s, he said, is that for high-income countries in the north, it appears that impacts could be relatively minor as far out as the end of the century. Nordhaus also remarked that impacts of migration within and between countries as a result of climate change need more study and interdisciplinary research—this is overlooked in most models but could have significant consequences in developing countries especially.

Calculating benefits, or damages averted, is alternately referred to as calculating the social cost of carbon. There is not wide agreement on the social cost of carbon, and Francisco de la Chesnaye remarked that getting some sort of agreement will be quite difficult. It is often present as a range of values. Bill Nordhaus noted that the global equivalent of a carbon price currently is around $2 per ton. Even with some suggesting $30 per ton and others more than $100 per ton, the price needs to come up significantly. As we begin implementing carbon trading and can demonstrate that it is not detrimental to the economy, then it will be easier to ramp up the price. Joel Smith pointed out that analysts must give thought to what drives perceptions—it is not purely economics. Dallas Burtraw supported this observation and said that a limitation of current benefit analysis is that it does not account for the sovereign value consumers might place on non-use values on resources—issues such as species extinction hint at this. In focus groups, the thought of species extinction sent consumers' willingness to pay skyrocketing, but environmental economics cannot frame this response well. Leon Clarke also remarked that the Department of Defense is paying more and more attention to climate change. He said that citizens certainly pay a lot more for the military than would be economically attractive using any type of discount rate, and thus there seem to be non-economic assumptions when dealing with something that is viewed as an existential threat.

On the topic of valuing impacts across different regions and timeframes, Adele Morris questioned what could be drawn from the literature about revealed preferences concerning contemporaneous wealth redistribution. Richard Newell replied that Partha Dasgupta of Cambridge University has drawn a distinction between these sorts of transfers within time, across geographies, for things for which people do not feel a responsibility, such as a hurricane. People might, however, feel responsible for the fate of future generations where climate change is concerned (Dasgupta, 2007). Bill Cline's recent analysis of potential agricultural impacts suggests that damage will be greatest near the equator, i.e., in developing countries. Damage in Africa and Latin America could range from a 15 to a 30 percent reduction in agricultural potential, and losses in India could be even higher (Cline, 2007). Marilyn Brown mentioned a report by the National Conference of State Legislators that provided some estimates of more localized climate impacts and costs. Impacts at a state level could translate, for example, to displacement of public investments in other areas, a possibility that makes the issue more compelling. Brown commented that more research on such impacts would be valuable.

Catastrophic Damage

In the economic modeling community, catastrophic damage is often discussed in terms of a fat-tail distribution (as opposed to a normal distribution). Martin Weitzman at Harvard University has written extensively on the importance of this approach, and Bill Nordhaus borrowed a quote from Weitzman to summarize the point, "The catastrophic insurance aspect of a fat tail unlimited exposure situation could dominate basically everything: the discounting, the risk, and the consumption smoothing" (Weitzman, 2009). Nordhaus indicated that the challenge for the modeling community is to think about how and where this issue and situation apply, and the ramifications for analysis. Dimitri Zenghelis remarked that we do not know with precision what the world will look like in the future or which regions or groups of people will be most adversely affected, but we do know that there are possibilities for high-impact/low-probability events, and the potential for catastrophic risks is bound to be an essential part of assessing impacts of emissions reductions. Therefore, he believes it is essential to make value judgments—how to value nonmarket goods ranging from environmental concerns to war and conflict. There is no correct value judgment, and there will be different views on this.

Nordhaus outlined four major catastrophic risks that have emerged over the years in the literature: the reverse of the North Atlantic deep water circulation, melting of large ice sheets, abrupt climate change, and ocean carbonization. He warned that unmanaged ecosystems, such as the polar ice caps, are likely to be drastically impacted. He described a scenario in which the Greenland ice sheet for example, could reach a tipping point, meaning that consequences would potentially be irreversible (Figure 4). These types of issues will require better integration of geophysical and economic modeling. Joel Smith agreed that damage to unmanaged ecosystems could potentially be the most significant consequence of climate change. He advised caution when attempting to assign value to occurrences like species or ecosystem loss—applying existing tools and frameworks may not be appropriate for challenges of this magnitude. He also mentioned the ongoing inquiry into the potential effects of sea surface warming on hurricane formation—one study pointed to $10 billion to $20 billion a year in additional damage by 2080 (ABI, 2005). In an analysis of costs for storm water systems in a city in Honduras, Joel and colleagues found that, under an assumption of a reasonably high level of change in intensity and amount of rainfall by 2025, infrastructure costs could increase by as much as 30 percent.

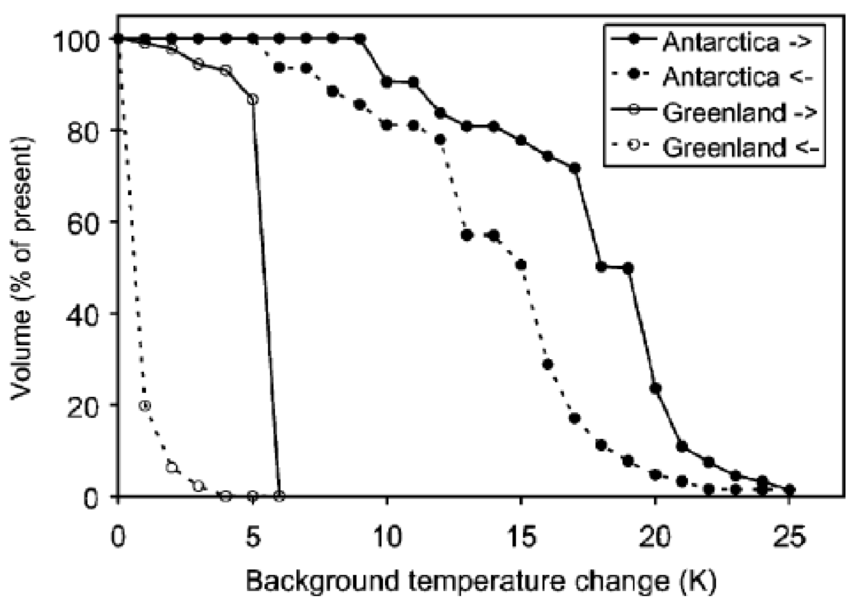

FIGURE 4. Hysteresis loops for ice sheets and “tipping points.” SOURCE: Pattyn, 2006. Copyright 2006. Reprinted with permission of Elsevier.

Policy Assumptions and Interactions

John Weyant explained that policy formulation indeed has a large effect on modeling results, and cost projections vary depending on the policy regime employed. Experiments in this area initially led Howard Gruenspecht to coin the term “where and when flexibility,” which refers to allowing for interregional and intertemporal trading. Adding to this uncertainty is the fact that cost projections are very dependent on policy assumptions: even when policy formulation is controlled for and the range of modeling results is thus narrowed, cost projections still assume that policies will be adopted and implemented in a rational and efficient manner. While analyzing options for California’s renewable portfolio standard (RPS) of 33 percent, Weyant and the rest of the Technical Advisory Committee stated that the first task would be to streamline siting, permitting, and transmission access. He also remarked on the numerous marginal cost curves that have shown negative costs, for electric utilities, industries, and the transportation sector, many of which represent efficiency opportunities. However, Weyant offered two cautions about these: (1) they generally use one baseline and so may be too simplistic, and (2) we do not fully understand the potential for decoupling in the electricity sector, and many of the efficiency opportunities seem to depend on decoupling being widely adopted. Despite these uncertainties, though, Weyant contends that it is possible to put rough bounds on policies and then rank them to aid policymakers.

Weyant went on to caution that policymakers should not, in an area with great complexity and uncertainty such as climate change, always opt for the solutions coming from a deterministic and long-term model, as these are likely to leave out important factors as time unfolds. Instead, it would be wise to do what is known to be necessary, and scale up or replicate what works and eliminate what does not. This also makes the case for taking action on the negative cost and other low-cost options immediately instead of delaying all action until there is wider agreement on an optimal stabilization number.

Richard Bradley spoke extensively about the important issue of capital turnover. He noted that policymakers *and* energy investors tend to have short time horizons (20-30 years)—an important point to keep in mind because, in the energy sector, capital turnover is going to be a critical issue and will need to occur on an enormous scale. Modeling microeconomic behavior could help answer questions about facility refurbishment and tear-down. An IEA study examining the role of carbon price in the timing of investments suggested that energy price uncertainty dominates carbon price uncertainty, save for a few sets of technologies (IEA, 2007). One of the most important actions a government can take, in that regard, is to extend commitment periods (e.g., from 5 to 10 years). IEA's analysis indicated that after about 15 years, investors were less concerned. Another important consideration, he said, is that no matter what becomes of power plant sites, energy investors do not easily relinquish the sites because they have already passed local ordinances, shortening the investment period for new construction. The reality, however, is that as fossil fuel plants close, the sites will not automatically be turned over to plants for generating power from renewable resources, due both to resource location and the anecdotal evidence that new technologies move into new demand areas as opposed to replacing existing demand.

Discounting

Bill Cline, Dimitri Zenghelis, and Bill Nordhaus all explained that the discounting rate one uses when making estimates has a large influence on estimated costs of mitigation. Cline remarked that in many climate change analyses, the cards are stacked against aggressive action based on the discounting rate chosen more so than by the adoption of modest damage estimates. He believes that the problem should be analyzed on a time scale of at least two centuries—discounting over this time frame has an overwhelming influence, and so he recommended opting for the social rate of time preference. Evidence suggests that an elasticity of marginal utility of 1.5 is close in conformity to what is observed in tax structures. He provided the caveat that one needs to shadow the price of capital when taking this rate, but his bottom line was that for about a half a percent of world product over the next 50 years we can purchase an insurance policy that leads to something close to two degrees of warming. This, he concluded, is a "cheap price for climate insurance."

Zenghelis explained the issue in terms of risk and value judgments. The important analysis now is in looking at how to apply conclusions in developing a global response effectively, so that it reduces risk efficiently, cost effectively, and equitably, so that parties are less likely to reject any sort of deal. One important value judgment is how to value people of different incomes across time and space—the intuition behind this is something that ought to be accessible to policymakers, not simply reduced to economics jargon. We know we value an impact on low-income people more than wealthy people, and this has consequences in terms of how one assesses risk. If one is risk averse, then more emphasis is placed on catastrophic impacts—the Stern Review used multiple discount rates to reflect different levels of risk aversion. Since climate change is stochastic and not deterministic, a single discount rate may not be appropriate.

The other big value judgment, according to Zenghelis, is in pure rate of time preference—market rates of return are the consequence of individual agent relative decisions, which are not necessarily appropriate to apply in valuing effects on future generations. A more appropriate rate seems to be close to the risk-free treasury bill rate. Zenghelis also stated that the non-marginality of climate change is also significant—there is no option for countries to put money in the bank and, instead of investing early in abatement, take it out hundreds of years from now to buy off the consequences, some of which are irreversible. Investors could be locked-in to backing high-carbon pathways and potentially facing catastrophes. The bottom line is that strategies that slowly ramp up may involve taking large, potentially irreversible risks.

Nordhaus explained that we know that addressing climate change is a global public good and that it involves millions of firms, thousands of different governments, and billions of people, all of which have to face realistic market prices. He also reiterated that new technologies and products need to be created by people in firms, and thus will be competing in the marketplace. Thus, he contends that analysts have to deal with the issue of at least a market rate of return as a benchmark for current policy, because investments in mitigation will be competing with other investments in other areas. He said that an important question for consideration is whether investments in mitigation are truly risk-free investments. Richard Newell remarked that Martin Weitzman discussed in his research how the combination of market- and non-market-based costs might lean toward a risk-free rate of return. In Nordhaus's own analysis, returns on investments in mitigation correlated positively with returns in general, indicating that a full-risk discount is appropriate. This area needs more research before decisions can be made on taking a risk-free versus full-risk discounting approach. Ultimately, Nordhaus concluded, the discounting argument can be a red herring—a real challenge seems to be improving analysis of the impacts of the lower-probability outcomes.

Importance of International Participation

Building on participants' earlier comments about the need for global participation in mitigation efforts, Bill Nordhaus described the cost of non-participation and its centrality to mitigation policy. Models have shown that the penalty cost function is enormous—top-down models indicate a larger penalty than bottom-up models do, but all show substantial cost penalties as participation drops below 100 percent. He explained that this was intuitive to economists but that he was surprised by the enormity of the importance of participation. He concluded that to be economically efficient, mitigation approaches need to be universal and harmonized across sectors and countries. Rick Bradley also pointed out that policymakers at the international level are looking for guidance on designing a phase-in strategy to eventually engage all countries in GHG reductions. Bill Cline stated that the prospective future damage from global warming warrants aggressive abatement action, and there is a solid economic case for a goal of 50 percent reductions by 2050. An important caveat is that although reaching the goal requires participation, the distribution of emissions is sufficiently concentrated that engaging countries like Brazil, China, India, and Russia will go a long way toward achieving that goal.

5
Enhancing Analytical Capabilities

The final discussion panel was organized to take stock of the current suite of analytical approaches for responding to policymaking informational needs, reflecting on the previous day's discussions. Panelists explored how existing models and analytic approaches could be improved, suggested specific areas that might deserve more focus, discussed new approaches worthy of further consideration, and highlighted opportunities for government agencies and other institutions to enhance their policy-analytic capabilities. Panelists were Ed Rubin, Carnegie Mellon University; John "Skip" Laitner, American Council for an Energy Efficient Economy (ACEEE); Nebojsa Nakicenovic, International Institute for Applied Systems Analysis; David Montgomery, Charles River Associates (CRA) International; Brian Murray, Duke University; Bryan Hubbell, U.S. Environmental Protection Agency; and Ray Kopp, Resources for the Future. John Weyant moderated the subsequent discussion and guided participants to think strategically about how existing resources in the analytical community could be used more efficiently, and also what might be done with a modest amount of additional resources. This chapter summarizes the major themes raised by the panelists and carried over into the group discussion.

Modeling Technological Change

Over the long run, how technological change is treated is a central issue to modeling. Bill Nordhaus said that the Monte Carlo runs on his last DICE model showed that technological change—both in the general sense as it affects the economy, and among different carbon-saving technologies—was the major uncertain variable. He also outlined three approaches to representing technological change and stated that its representation is the single most unsatisfactory element in models: exogenous change, technological learning, and the Romer model. Exogenous technical change, projections based on historical trends, was the industry standard until the late 1990s, but the obvious problem is that as soon as one introduces changes in prices, particularly the price of carbon relative to other input prices, then technological change is induced.

The learning-by-doing approach can be attractive for modelers because it is simple and requires little data. However, Nordhaus and several other participants pointed to problems with this approach. The econometric literature suggests that use of simple bivariant coefficients can lead to an upward bias of the learning coefficient (e.g., Berndt, 1991). It is even more problematic if used in an optimization model, because it ultimately leads to an overadaptation by learning technologies (those assumed to improve with experience over time) relative to non-learning technologies. Ed Rubin seconded this observation and pointed out that historical analysis has shown that costs can often go up considerably before they go down. Graham Pugh of DOE noted that learning curves tend to focus on applied R&D but leave out potential game-changing solutions that require basic research. Richard Newell noted that, when learning curves are plugged into an optimization model, the model is not accounting for the opportunity costs of learning in one sector versus another—learning in a renewable energy technology may mean learning less in nuclear or clean-coal power, for example. Marilyn Brown added that for energy technologies, some will need next-generation approaches, making it unrealistic to expect staying on a steady learning curve. Nebojsa Nakicenovic added that these learning curves are used mechanistically, even though we do not understand the details and processes behind the curves. Figure 5 shows that technology cost curves are not all uniform. Analyses generally utilize curves that indicate large improvements over time. However, several

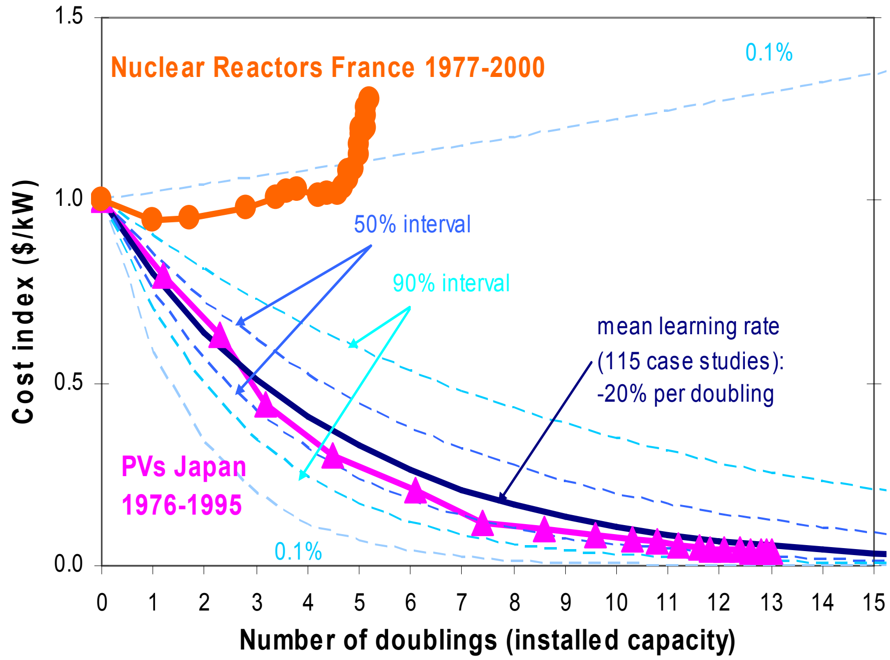

FIGURE 5. Technological uncertainties: learning rates (push) and market growth (pull). SOURCE: Nebojsa Nakicenovic, International Institute for Applied Systems Analysis, presentation given at the Workshop on Assessing Economic Impacts of Greenhouse Gas Mitigation, National Academies, Washington, D.C., October 2-3, 2008.

current technologies have instead seen limited improvement despite continuous investment. Therefore, Nakicenovic and Nordhaus both recommended doing sensitivity analyses with the learning off, to help bound expectations.

Finally, Nordhaus described a third approach, the Romer model (Romer, 1990), which in his view is the right kind of model. It has conceptual and data problems that need serious work, but it has an explicit link between R&D and other inputs and the technology outputs. David Montgomery agreed that a Romer-type model may be the appropriate one to use, but offered three concerns. First is that the process of basic research is not very clear or predictable. Second, we do not entirely know how efficient the market for innovations is. Third, it is not easy with this model to determine where the levers might be to influence the rate or direction of technological progress, in order to reduce GHG emissions, particularly given that the influence of prices on R&D decisions is not well understood.

Nakicenovic added that the lack of data may be the major constraint to using a Romer-type model. He pointed to a recent report that Germany and some other countries in Europe are expecting to increase energy R&D efforts after more than a decade of drastic declines—trying to understand what drives this apparent inducement of technological change will be key to modeling issues. Richard Newell seconded the notion that empirical data is a critical limitation and suggested that there is a major need for more work in theoretical development of ways to model technological change. He and colleagues are currently working on some aspects of this, such as understanding market imperfections and the effects of spillovers.

Skip Laitner concurred that the Romer model was an appropriate beginning point but cautioned that modelers still tend to have an outdated view of technology and ought to improve their understanding of 21st century technologies. Inja Paik noted that the OECD has done a considerable amount of work in examining national innovation systems, how countries organize R&D resources to generate knowledge, and how diffusion of knowledge eventually contributes to their GDP. This work seems to have implications for the Romer model approach. Newell added that it continues to be difficult to evaluate prospective benefits from R&D investments without being able to model these in much more detail than is currently possible.

Complementary Components

As Marilyn Brown remarked, it seems to take a suite of models to examine the complexities of the numerous policy interactions. Several participants discussed early ongoing efforts to link models and address some of these issues. Three important issues that were continually cited as being critical to the ultimate success of mitigation efforts: offsets, transportation, and air quality.

Offsets

Brian Murray remarked that modeling has shown that offsets are critical to the cost of mitigation policies, but questioned how well offset programs were being modeled. A 2005 EPA analysis suggested that the largest source of offsets in the U.S. domestic market will come from agriculture and forestry (EPA, 2005). Analysts have attempted to incorporate some realism into their estimates, recognizing that certain activities may be slow to come to fruition. But there are several issues that bear watching, to improve understanding of the institutional realities of registering, establishing baselines, and certifying projects. He also underscored that opening up to the international market can reduce costs significantly (Figure 6)—much of this potential is in reducing deforestation in tropical countries. Tim Profeta echoed the need to understand the availability of offsets since this is a major determinant of cost, but he also advised caution when modeling international offsets, which requires an international infrastructure that is not yet ready to deliver. He also suggested that more work could be done to understand and then communicate the effect of delayed availability for domestic (U.S.) offsets.

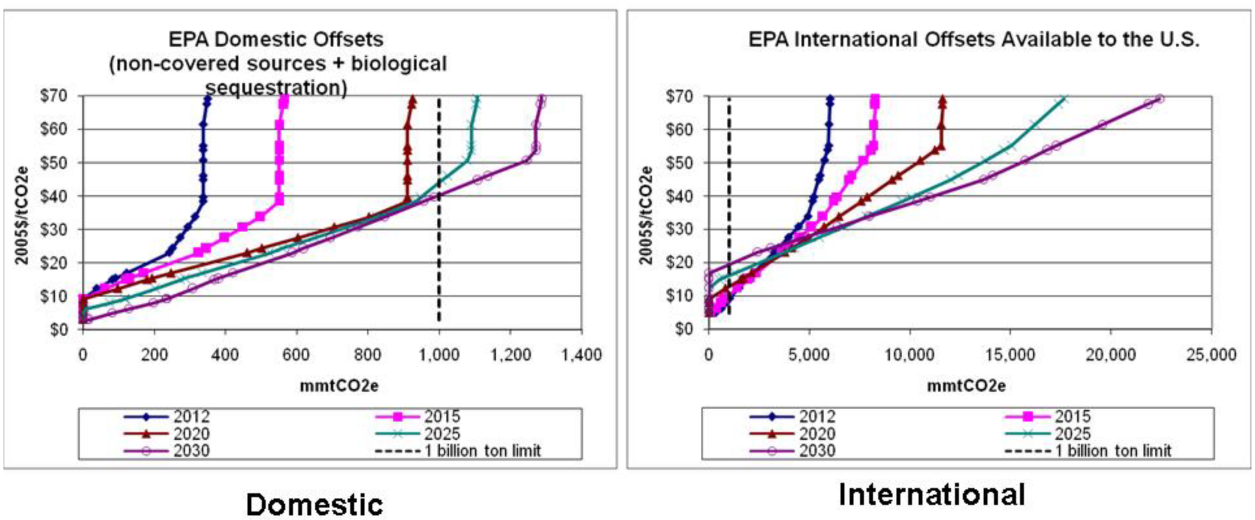

FIGURE 6. EPA estimates of GHG offset supply functions. SOURCE: EPA, 2005.

Brian Murray explained that the recent surge in biofuel production, and the targets that have been set in the United States out to 2030, have fundamentally altered the forest and agriculture models—these changes are significant enough to create problems for the mathematical programming framework underpinning the models. Bob Shackleton echoed the need for better information on availability and costs of offsets from a variety of sources of non-CO_2 GHGs—he stated that EPA's cost curves, which most modelers use, are a good foundation but are insufficient. According to CBO's recent analysis, 40 percent of GHG emission reductions were attributed to offsets, which lowered the carbon price by 30 percent, an issue that will be critical to moderating policy costs in the early years (CBO, 2008).

Transportation Sector

Reflecting on the various workshop participants' comments that transportation is likely to be treated differently from other energy-consuming sectors, Bob Marlay noted that transportation still seems to be stovepiped, perhaps more than other sectors, and while there has been much important work done in looking at the various components (roads, vehicles, batteries), there might be more value in viewing the sector as a system, particularly given that the sector is one of the main leverage points in achieving an emissions-free economy. Brian Murray wondered if modelers could improve how they capture the transportation sector in their models. In general, he pointed out that models tend to focus on fuel economy standards but do not generally reflect responses to a carbon price.

Air Quality

Bryan Hubbell explained that there are potential interactions and efficiencies to be had in integrating air quality and climate modeling. Due to the magnitude and immediacy of air-pollution-related health effects, it is also important not to forget that there are existing air quality goals that we will continue pursuing as we begin to address climate change issues. Timing and spatial location will be important considerations, because when considering GHG emission reductions, there are potential co-benefits to reducing criteria air pollutants, depending on location.

EPA's Office of Air Quality Planning and Standards (OAQPS) normally deals with sector-level models but is investigating ways to link these to macro models by developing models that communicate with one another, sending carbon prices down or sending technology/production constraints up (Figure 7). Its industrial sectors integrated solutions model (ISIS) will be linked directly to ADAGE, but also linked through MARKAL, which will act as a bridge between ADAGE and the sector-specific outputs for technology and emissions, along with the air quality impacts fed back from ADAGE's outputs. EPA has also been developing a control strategy tool (CoST), which is a database of control strategies for criteria pollutants and toxics, along with cost curves and associated emission reductions. OAQPS is working on adding GHG control technologies and is also cooperating with the Office of Atmospheric Programs to develop closer linkages between benefits assessments and large-scale CGE modeling.

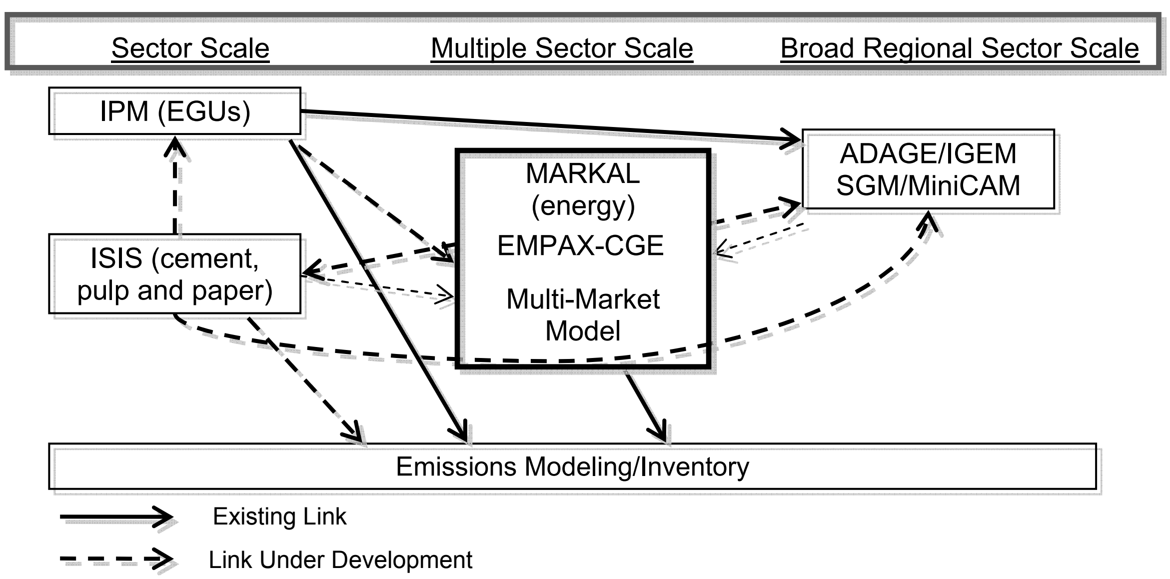

FIGURE 7. Multiscale assessment: point-sources. SOURCE: Bryan Hubbell, U.S. Environmental Protection Agency, presentation given at the Workshop on Assessing Economic Impacts of Greenhouse Gas Mitigation, National Academies, Washington, D.C., October 2-3, 2008.

Data and Functional Needs

Ray Kopp described a model as having three major components underpinning it: theory, data, and functional relationships. The theory, which gives rise to the structure of the model and provides consistency, coherence, and explanatory power, has made good progress over the years, likely because it is rewarded within the academic community. On the data side, there has also been progress. There has tended to be government funding available to support the compilation of databases, such as GTAP, which are valuable to economists and modelers. However, when one examines the functional relationships (e.g., utility functions, production functions), there has been substantially less progress. In many cases, modelers are left to use functions that might be 30 or 40 years old. In the 1970s when many of these functions were being developed, there was funding to support the research, and the work was getting published and thus rewarded. This is not the case today, and so modelers are using old econometric estimates, or attempting to apply estimates from one sector to another. There is a need for more empirical study to support all of these parameters, to provide insight into the important elasticities associated with factors like technological progress.

Kopp emphasized that there is also a need for more attention to terrestrial carbon, and forest carbon in particular. Policymakers will be raising questions about supply curves for forest carbon, how a forest carbon market would affect food or biofuel markets, and how a global carbon market could help incentivize forest management and land-use decisions. This then highlights the importance of spatial analysis, and also the challenge of linking spatially based land-use models with larger-scale macroeconomic models, which tend to treat space abstractly. There is a lot of methodological work that needs to be done to take high-quality land-use models and link them so that large-scale macroeconomic models can reference them.

Ed Rubin emphasized that a fundamental challenge continues to be how to employ models that are behaviorally realistic. He suggested that it requires beginning with observations, and then equations, and that over decades these will be refined. It is also crucial to engage a broader spectrum of disciplines beyond economics, and Rubin urged that sustained institutional support is necessary to reward interdisciplinary activity. He remarked that the ability to create and implement analytical models and theoretical constructs far outstrips the availability of empirical data to rigorously test these constructs—creative experiments and historical data analysis, which he and colleagues have done in looking at technological learning curves, will help verify functions. He also envisioned a hierarchy of models, noting that no one model is best suited to answer the diverse array of questions that policymakers and other interested parties will ask. Bryan Hubbell pointed out that EPA has done a lot of thinking about energy efficiency, and specifically why existing opportunities are not being adopted. There are clearly behavioral issues, but these need to be parsed out, and he also suggested that consideration be given to the limitations on the human capital side, like education and training and other workforce needs.

Skip Laitner remarked that technology and behavioral aspects of modeling have been ignored for too long. He offered four suggested areas for improvement: (1) technology characterization on the supply and demand side; (2) capital flows that better distinguish between energy and nonenergy investments and highlight important differences between, for example, information and communication technologies versus metal foundries or papermaking; (3) modeling assumptions about consumers and firms which reflect actual behavior and shifting preferences—price elasticities are at such a high level that they can miss critical information, such as the degree to which consumers are informed or motivated, or the influence of habits and necessity on response to prices; and (4) economic accounting of investments in technologies, to highlight the significant returns on certain investments. He stressed that prices matter, but they are not all that matters and more could be done to tease out these other points to help inform policymakers. He further noted that CGE representation may be an inappropriate characterization of technology, overestimating the costs of adopting a technology. Industries have several different elasticities of substitution, far more than are represented in most models. There is also a need for investigation into behaviors such as how substitutions evolve in response to improved information and technological advances.

Richard Newell remarked that much of the analytical work that has been done to date has been complicated by the absence of a carbon price, making it difficult to model behavior in the absence of direct empirical evidence of how actors will respond. Thus, a carbon price should also help improve analysts' ability to model behavior into the future.

Nebojsa Nakicenovic commented that integrated assessment modeling has made huge progress over the last 20 years and has had success in integrating economics with technological perspectives, demographics, and other human dimensions, and then linking all of this to climate models. Where it has been less successful is in folding in impacts and possible adaptation measures. He outlined three areas in need of improvement: (1) dealing with uncertainty, about both technologies and policies—there are no tools to adequately consider low-probability but highly consequential events; (2) analyzing failures, which would provide valuable insight into ways to support R&D efforts—specifically, how does one measure the success of R&D, particularly at the early deployment stage? and (3) heterogeneity of decisionmakers—regionally and sectorally, agents will behave differently, but this heterogeneity is not well reflected in most models.

Finally, as was stressed during the discussion of current analytical capabilities, workshop participants pointed out that there is a pressing need for more regional and household-level data. Regional data is essential to successfully integrating air-quality and land-use models. Recognizing that end users are increasingly requesting detailed outputs (e.g., state-level employment impacts), participants emphasized that the quality and confidence level of such outputs will depend on improved data sets. Participants also noted that international data sets can be of poor quality and difficult to obtain, but nonetheless they are crucial to global modeling efforts.

Institutions and Innovation

David Montgomery remarked that existing models are effective for modeling idealized policies, but these do not reflect the real world. He outlined three shortcomings: failure to consider institutions; grossly underestimating the costs of inefficient nonmarket policy initiatives that are already coming into effect; and not adequately addressing the R&D and innovation process. Processes such as institutional change and innovation are not represented structurally in the models, nor are they generally predictable or controllable, but as one models out through 2050 or 2100, these processes are almost the entire story.

Montgomery contended that modeling global costs requires understanding how the institutional settings in different countries will limit the efficiency of policies and the feasibility of achieving emissions reductions—the rule of law and the existence of economic and political freedom are factors that will have an impact but are not modeled.

On a related point, modeling policies in the United States, Canada, and the European Union requires also being able to model the perverse incentives and unintended consequences of command and control regulations, technology mandates, and targeted subsidies. The field of regulatory economics, however, does have a long and solid history of analyzing the implications of regulatory programs and perverse incentives, and so a dialogue between the modeling community and those who study institutions may be beneficial.

Montgomery also advised that no model will ever capture all of the ways that a smart economic agent can find to circumvent regulations, which can raise costs and diminish a program's effectiveness. He pointed to a large body of literature (e.g., Cohen and Noll, 1991) dedicated to characterizing the history of R&D and demonstration projects and the role of government. Models do not provide the kind of insight that would inform the design of R&D policies.

Bill Nordhaus stressed that intellectual property rights will be another key component, and reiterated that there are limited instruments (e.g., an aging patent system) to address this. He then raised the question of whether or not climate change is somehow different from other sectors, or is it possible to look to sectors such as health or telecommunications. Marilyn Brown cited a CCTP report (Brown et al., 2006) that analyzed the disciplines that are most critical to the key technology areas looking at climate solutions. She emphasized that there were no new disciplines in that list, and she suggested that climate change is perhaps marginally different from other topics of study, but does not necessarily require different disciplines or fundamentally different approaches, merely more sustained efforts at interdisciplinary work.

Nordhaus also noted that more consideration must be given to the complementarities between public and private R&D, both in terms of synergy and also whether or not public R&D may crowd out some private R&D. John Weyant suggested that there may be lessons in looking at other innovation systems, such as the National Institutes of Health (NIH). Weyant also pointed out that there are certain gaps in the innovation chain that are not filled because they fall between basic science research and venture capital opportunities, since venture capitalists tend not to take large technological risks. On the subject of risk, Nakicenovic mentioned that IIASA has used its mathematical MESSAGE model to treat uncertainty explicitly with regard to technology investment risk. An assumption was that investors were willing to pay a risk premium to hedge against some of that risk—as the risk premium approaches 5 percent, the dynamics of the entire system fundamentally change. Investments in the lower-cost options start to happen earlier and there will be more diversity in terms of technologies, and the more costly and risky technologies get introduced as well. Weyant also mentioned that in the field of robotics, most big innovations are based on a series of old patents, with one or two new patents building on these to lead to breakthroughs. He related this notion to the common conception of innovation being one of bold pathbreaking changes, which overlooks the minor breakthroughs that might bridge the gap enough to make new technologies commercially viable.

Bryan Hubbell relayed the anecdote of research funding for land grant universities working on genetically modified crops in the late 1980s and early 1990s—this basic research was designed to maximize spillovers and thus public benefit. However, as public funding tightened and then as public/private cooperatives emerged, the nature of the research changed to one that would minimize spillovers and thus allow private entities to capture the rents. He questioned whether or not this situation could be managed differently with regard to paradigm-changing energy and climate technologies. Adele Morris also noted the important linkage between R&D and international participation, specifically that there are potentials for international spillovers, and this information could inform international negotiations with an eye toward maximizing the global impact of such spillovers.

Skip Laitner mentioned that Moore's law is not a physical law, but an extrapolation that has become a self-fulfilling prophecy that continues to be driven by business models. Graham Pugh concurred and noted that there may be lessons from the semiconductor industry's experience with the research collaborative Sematech. Sematech is a pre-competitive R&D consortium, whereby leading semiconductor companies pooled resources and worked collaboratively. From the industry point of view, the costs were too great to be borne by any one company, and this collaborative effort allowed them to move toward the production frontier in a pre-competitive model, driven by the perceived need for constant innovation.

Communicating Results

To conclude the workshop, participants discussed how to take ideas forward and improve communication channels between policymakers and the analytical community. As Francisco de la Chesnaye and others remarked, it is incumbent on analysts to spend more time comparing and synthesizing similar analyses to better communicate their insights. A participant questioned whether reduced-form models that could be operated by congressional staff or other lay people might be useful, but Dick Goettle replied that after 20 seconds, a consumer would begin asking the detailed questions that only the more-complicated models can answer. Computer time is cheap and there are good models out there, and so he advised that the full-form models be run.

Ed Rubin's simple advice to analysts was to "get the sign right," a reference to the need to better communicate where and why there are negative cost opportunities to be had. This message seems to get lost when discussing the overall costs to the economy.

David Montgomery expressed concern that, since they are not taking full account of the institutional impediments and inefficiencies that may drive up costs, the models are all projecting costs on the low end of what may in fact occur. Skip Laitner agreed that the results are likely the lower bound of costs, but he also argued that there are benefits in terms of productivity gains, efficiency gains, spillover innovation, and other aspects that are also not fully accounted for. Thus, he commented, more work needs to be done on characterizing full costs and full benefits. Richard Newell offered the caution that there needs to be a distinction between hypothetical opportunities and those that can be captured given existing conditions (including institutional impediments and regulations).

John Weyant described the current situation in California, where analysts are trying to reframe the notion of "cost-effective" from zero or negative cost options to least-cost options to achieve whatever objectives policymakers think they need to achieve. In other words, there is recognition that addressing climate change entails additional costs, and while there is uncertainty about those costs, this should not be a deterrent to taking early action. One additional challenge he described is the cost shock that could pose a political risk—policies could cost much more than anticipated, and rate shock for consumers could undermine further progress.

Select Bibliography

ABI (Association of British Insurers). 2005. Financial Risks of Climate Change, Summary Report. London, U.K.: ABI. June.

Berndt, E.R. 1991. The Practice of Econometrics: Classical and Contemporary. Reading, Mass.: Addison-Wesley Publishing Company.

Brown, M.A., M. Antes, C. Franchuk, B.H. Koske, G. Michaels, and J. Pellegrino. 2006. Results of a Technical Review of the U.S. Climate Change Technology Program's R&D Portfolio. ORNL-6976. Oak Ridge, Tenn.: Oak Ridge National Laboratory, U.S. Department of Energy. May.

CBO (Congressional Budget Office). 2008. Cost Estimate for S. 2191: America's Climate Security Act of 2007. Washington, D.C.: CBO. April 10.

CCTP (U.S. Climate Change Technology Program). 2006. Strategic Plan. Washington, D.C.: CCTP. September.

Cline, W.R. 2007. Global Warming and Agriculture: Impact Estimates by Country. Washington, D.C.: Center for Global Development and Peterson Institute for International Economics.

Cohen, L.R., and R.G. Noll. 1991. The Technology Pork Barrel. Washington, D.C.: The Brookings Institution.

Dasgupta, P. 2007. Discounting Climate Change. Cambridge, U.K.: University of Cambridge. Revised March 2008.

den Elzen, M., P. Lucas, and D. van Vuuren. 2008. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO_2-equivalent. Climatic Change 90(3).

EPA (Environmental Protection Agency). 2005. Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture. EPA 430-R-05-006. Washington, D.C.: EPA Office of Atmospheric Programs. November.

EPRI (Electric Power Research Institute). 2008. EPRI Workshop on Cost Estimates of Lieberman-Warner Climate Legislation, Washington, D.C., May 8. Palo Alto, Calif.: EPRI.

Houser, T., R. Bradley, B. Childs Staley, J. Werksman, and R. Heilmayr. 2008. Leveling the Carbon Playing Field: International Competition and U.S. Climate Policy Design. Washington, D.C.: Peterson Institute for International Economics and World Resources Institute. May.

IEA (International Energy Agency). 2007. Climate Policy Uncertainty and Investment Risk. Paris, France: OECD/IEA.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: IPCC Fourth Assessment Report (AR4). Cambridge, U.K.: Cambridge University Press.

Lempert, R.J., S.W. Popper, S.A. Resetar, and S.L. Hart. 2002. Capital Cycles and the Timing of Climate Change Policy. Washington, D.C.: Pew Center on Global Climate Change. October.

McKinsey & Company. 2007. Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost? New York, N.Y.: McKinsey & Company.

Murray, B.C., R.G. Newell, and W.A. Pizer. 2008. Balancing Cost and Emissions Certainty: An Allowance Reserve for Cap-and-Trade. RFF Discussion Paper 08-24. Washington, D.C.: Resources for the Future. July.

Nordhaus, W. 2008. A Question of Balance: Weighing the Options on Global Warming Policies. New Haven, Conn.: Yale University Press.

NRC (National Research Council). 1992. The National Energy Modeling System. Washington, D.C.: National Academy Press.

Pattyn, F. 2006. GRANTISM: An ExcelTM model for Greenland and Antarctic ice-sheet response to climate changes. Computers & Geosciences 32:316-325.

Paul, A., D. Burtraw, and K. Palmer. 2008. Compensation for Electricity Consumers under a U.S. CO_2 Emissions Cap. Discussion Paper 08-25. Washington, D.C.: Resources for the Future.

Richels, R., J. Edmonds, H. Gruenspecht, and T. Wigley. 1996. The Berlin Mandate: The Design of Cost-Effective Mitigation Strategies. Report of the Subgroup on the Regional Distribution of the Costs and Benefits of Climate Change Policy Proposals, Stanford University Energy Modeling Forum 14. Stanford, Calif.: Stanford University.

Romer, P.M. 1990. Endogenous technological change. Journal of Political Economy 98(5).

Stern, N. 2007. The Economics of Climate Change: The Stern Review. Cambridge, U.K.: Cambridge University Press.

Sterner, T.A., and U.M. Persson. 2007. An Even Sterner Review: Introducing Relative Prices into the Discounting Debate. RFF Discussion Paper 07-37. Washington, D.C.: Resources for the Future. July.

Webster, M., S. Paltsev, J. Parsons, J. Reilly, and H. Jacoby. 2008. Uncertainty in Greenhouse Emissions and Costs of Atmospheric Stabilization. Report No. 165. Cambridge, Mass.: MIT Joint Program on the Science and Policy of Global Change.

Weitzman, M.L. 2009. On modeling and interpreting the economics of catastrophic climate change. The Review of Economics and Statistics 91(1).

Appendixes

A
Workshop Agenda

October 2-3, 2008
Embassy Suites Hotel, Capital Room A
900 10th St NW, Washington, D.C.

Workshop objective: Identify decisionmaking needs, capabilities, and opportunities for advancing the capacity for economic analysis of climate policies, including guiding future investments in the U.S. federal R&D portfolio.

OCTOBER 2, 2009

8:30 am **Welcoming Remarks and Goals of the Workshop**

Richard Newell, Gendell Associate Professor of Energy and Environmental Economics, Duke University
Robert Marlay, Deputy Director, Office of Climate Change Policy and Technology, U.S. Department of Energy

Session I: Policymakers' Informational Needs (Richard Newell)

9:00 am **Panelists from Government and the Policy Community**

This panel will identify the range of specific informational needs and questions regarding the design, impacts, and outcomes of climate change policies and related energy policies that are being asked, or are likely to be asked in the future, by policymakers.

Bob Shackleton, Congressional Budget Office
Howard Gruenspecht, Energy Information Administration
Francisco de la Chesnaye, Electric Power Research Institute
Nat Keohane, Environmental Defense Fund
Tim Profeta, Duke University

10:10 am **Broader Group Reactions, Questions, and Discussion**

Session II: Modeling and Other Analytic Approaches (Marilyn Brown)

11:00 am *This panel will present many of the existing modeling and other analytic approaches currently being used to meet the type of informational needs explored in Session I. Rather* *than focusing on specific modeling results, panelists will present the capabilities and high-level structure of specific types of models/analytic approaches, advantages/disadvantages relative to other approaches, how decisionmakers are using these tools, whether/how the approaches incorporate uncertainty, and other related issues.*

John Conti, Energy Information Administration
Dick Goettle, Northeastern University
Leon Clarke, Pacific Northwest National Laboratory

Questions from Audience

Martin Ross, RTI International
John Reilly, Massachusetts Institute of Technology
Jean-Marc Burniaux, Organisation for Economic Co-operation and Development

Questions from Audience

Tom Kram, Netherlands Environmental Assessment Agency
Dallas Burtraw, Resources for the Future
Peter Evans, GE Energy

Questions from Audience

2:10 pm **Broader Group Reactions, Questions, and Discussion**

Session III: Economics of GHG Mitigation and Climate Change (Richard Newell)

3:00 pm **Economic Modeling and Policy for Global Warming**

William Nordhaus, Sterling Professor of Economics, Yale University

3:30 pm **Panel Discussion: Critical Assumptions, Advantages, and Limitations**

This panel will explore the state of the economics of climate change, and the role of economic analyses in climate policy decisionmaking. Panelists will discuss key modeling assumptions, advantages, and limitations, potential impacts to the U.S. and world economies, approaches for estimating benefits and costs of mitigation, and the intertemporal and distributional equity issues associated with climate change and mitigation.

John Weyant, Stanford University
Joel Smith, Stratus Consulting Inc.
Richard Bradley, International Energy Agency
Dimitri Zenghelis, London School of Economics
William Cline, Peterson Institute for International Economics

4:30 pm **Broader group reactions, questions, and discussion**

5:30 pm **Closing Comments and Charge for Day Two**

OCTOBER 3, 2008

8:30 am **Summary of Day One**

Session IV: Enhancing Analytical Capabilities to Inform Policy (John Weyant)

8:40 am *This panel will take stock of the current suite of modeling/analytical approaches for responding to policymaking informational needs. Panelists will explore how existing models and analytic approaches could be enhanced, specific areas that might deserve more focus (e.g., uncertainty, technology policy, risk, international analyses, interactions with other policy goals), new approaches worthy of further development, and opportunities for government agencies and other institutions to enhance their policy-analytic capabilities.*

Brian Murray, Duke University
Ray Kopp, Resources for the Future
Ed Rubin, Carnegie Mellon University
Bryan Hubbell, U.S. Environmental Protection Agency
Skip Laitner, American Council for an Energy Efficient Economy
Nebojsa Nakicenovic, International Institute for Applied Systems Analysis
David Montgomery, CRA International

10:20 am **Broader Group Reactions, Questions, and Discussion**

12:00 pm **Summary and Wrap-up**

B
Speaker and Panelist Biographical Information

Richard G. Newell is the Gendell Associate Professor of Energy and Environmental Economics at the Nicholas School of the Environment, Duke University. He is a research associate of the National Bureau of Economic Research and a university fellow of Resources for the Future. He has served as the senior economist for energy and environment on the President's Council of Economic Advisers, where he advised on policy issues ranging from automobile fuel economy and renewable fuels to management of the Strategic Petroleum Reserve. He has been a member of expert committees including the National Research Council Committee on Energy Externalities, Committee on Energy R&D, Committee on Innovation Inducement Prizes, and Committee on Energy Efficiency Measurement Approaches. Dr. Newell also served on the 2007 National Petroleum Council Global Oil and Gas Study. He currently serves on the boards of the *Journal of Environmental Economics and Management*, the journal *Energy Economics*, the Association of Environmental and Resource Economists, and the Automotive X-Prize. He has served as an independent expert reviewer and advisor for many governmental, non-governmental, international, and private institutions including the OECD, Intergovernmental Panel on Climate Change, World Bank, National Commission on Energy Policy, U.S. Environmental Protection Agency, U.S. Department of Energy, U.S. Energy Information Administration, U.S. National Science Foundation, and others. Dr. Newell received his Ph.D. from Harvard University.

Marilyn A. Brown joined the Georgia Institute of Technology in 2006 after a distinguished career at the U.S. Department of Energy's Oak Ridge National Laboratory (ONRL). At ORNL, she held various leadership positions and led several major energy technology and policy scenario studies. Recognizing her stature as a national leader in the analysis and interpretation of energy futures in the United States, Dr. Brown remains affiliated with ORNL as a visiting distinguished scientist. Recent projects include an assessment of the $3 billion/year multi-agency R&D portfolio comprising the U.S. Climate Change Technology Program, development of a national climate change technology deployment strategy as required by the 2005 Energy Policy Act, and quantification of the carbon footprints of the nation's largest 100 metropolitan areas. Dr. Brown has been an expert witness in hearings before Committees of both the U.S. House of Representatives and the U. S. Senate. She serves on the board of directors of the Southeast Energy Efficiency Alliance, the American Council for an Energy-Efficient Economy, and the Alliance to Save Energy; she is on the editorial boards of several journals including the *Journal of Technology Transfer*. She is a member of the National Commission on Energy Policy and the National Academies' Board of Energy and Environmental Systems, and she is a co-recipient of the 2007 Nobel Peace Prize, among other awards. She received her B.A. in political science from Rutgers University (1971), her M.R.P. in resource planning from the University of Massachusetts (1973), and her Ph.D. in geography from Ohio State University (1977). She is also a Certified Energy Manager.

John Weyant came to Stanford University in 1977, primarily to help develop the Energy Modeling Forum. Dr. Weyant was formerly a senior research associate in the Department of Operations Research, a member of the Stanford International Energy Project and a fellow in the U.S.-Northeast Asia Forum on International Policy. He is currently an adviser to the U.S. Department of Energy, Pacific Gas & Electric Company, and the U.S. Environmental Protection Agency. His current research is focused on global climate change, energy security, corporate strategy analysis, and Japanese energy policy. He is on the editorial boards of *The Energy Journal* and *Petroleum Management*. His national society memberships include the American Economics Association, Association for Public Policy Analysis and Management, Econometric Society, International Association of Energy Economists, Mathematical

Programming Society, ORSA, and TIMS. He received his B.S. and M.S. in aerospace engineering and astronautics and an M.S. in operations research and statistics from Rensselaer Polytechnic Institute, and his Ph.D. in management science from the University of California, Berkeley.

Richard Bradley has been the head of the Energy Efficiency and Environment Division (EED) at the International Energy Agency in Paris since 2004. The EED provides analytical support to the IEA Standing Group on Long Term Co-Operation and to the Annex I Experts Group on a range of climate change and energy efficiency policy issues. For many years, he represented the United States as a senior negotiator on multilateral energy and environment agreements. He is also a former chair of the OECD/IEA Annex I Experts Group. He has written a number of articles on climate change issues.

Dallas Burtraw's research interests include the design of environmental regulation, the costs and benefits of environmental regulation, and the regulation and restructuring of the electricity industry. Recently, Burtraw investigated the effects on the value of assets of electricity generation companies of alternative approaches to implementing emissions permit trading programs. He is evaluating the use of emission trading to achieve carbon emission reductions in the European Union. He also has helped to evaluate the cost-effectiveness of trading programs for nitrogen dioxide in the eastern United States and sulfur dioxide trading programs under the Clean Air Act Amendments. He also contributed to the valuation of the benefits of ecological improvements due to reduced acidification in the Adirondacks. Dr. Burtraw has a Ph.D. in economics (1989) and M.P.P. in public policy (1986) from the University of Michigan and has a B.S. in community economic development (1980) from the University of California, Davis.

Leon Clarke is a senior research economist at the Pacific Northwest National Laboratory (PNNL), and he is a staff member of the Joint Global Change Research Institute (JGCRI), a collaboration between PNNL and the University of Maryland at College Park. Dr. Clarke's current research focuses on the role of technology in addressing climate change, scenario analysis, and integrated assessment model development. Dr. Clarke coordinated the U.S. Climate Change Science Program's emissions scenario development process, and he was a contributing author on the Working Group III contribution to the IPCC's Fourth Assessment Report. Prior to joining PNNL, Dr. Clarke worked for RCG/Hagler, Bailly, Inc. (1990-1992), Pacific Gas & Electric Company (1992-1996), and Lawrence Livermore National Laboratory (2002-2003). He was also a research assistant at Stanford's Energy Modeling Forum (1999-2002), where he worked on issues related to technological change and integrated assessment modeling. Dr. Clarke received B.S. and M.S. degrees in mechanical engineering from University of California, Berkeley, and his M.S. and Ph.D. degrees in engineering economic systems and operations research at Stanford University.

William R. Cline, senior fellow, has been associated with the Peterson Institute for International Economics since 1981 and holds a joint appointment at the Center for Global Development. During 1996-2001 while on leave from the Institute, Dr. Cline was deputy managing director and chief economist of the Institute of International Finance (IIF) in Washington, D.C. The IIF conducts research on emerging-market economies for its membership of over 300 international banks, investment banks, asset management companies, insurance companies, and other financial institutions. He has been a senior fellow at the Peterson Institute for International Economics since its inception in 1981. Previously he was senior fellow, the Brookings Institution (1973-1981); deputy director of development and trade research, Office of the Assistant Secretary for International Affairs, U.S. Treasury Department (1971-1973); Ford Foundation Visiting Professor in Brazil (1970-1971); and lecturer and assistant professor of economics at Princeton University (1967-1970). He graduated summa cum laude from Princeton University in 1963 and received his M.A. (1964) and Ph.D. (1969) in economics from Yale University.

John J. Conti is the director of the Office of Integrated Analysis and Forecasting (OIAF) at the Energy Information Administration (EIA). His office is responsible for the domestic and international midterm energy projections and the Greenhouse Gas Program and publishes the *Annual Energy Outlook*, the *International Energy Outlook*, *Emissions of Greenhouse Gases in the United States*, and the *Voluntary Reporting of Greenhouse Gas Emissions.* In addition, due to the interest in the impact greenhouse gas mitigation policies on energy markets, his office has produced a number of special analyses for the U.S.

Congress. Mr. Conti has spent the past 28 years at the Department of Energy in the Office of Policy and International Affairs and the Energy Information Administration. Mr. Conti has a M.S. degree in management and policy sciences and an undergraduate degree in economics from the State University of New York at Stony Brook.

Francisco C. de la Chesnaye is a senior project manager in the Global Climate Change Program at the Electric Power Research Institute (EPRI). His current research portfolio covers both domestic and international climate change issues. On domestic issues, his work focuses on modeling of the U.S. energy system, in particular the U.S. electric power sector, to evaluate the possible transformation of the system under alternative policies. On international issues, Mr. de la Chesnaye's work is focused on analyzing post-2012 global climate change policies. Prior to joining EPRI, Mr. de la Chesnaye was the chief climate economist at the U.S. Environmental Protection Agency. He was responsible for developing and applying EPA's economic models for domestic and international climate change policy analysis. He led EPA's efforts to produce the agency's first independent economic analysis of a climate policy, the McCain-Lieberman bill of 2007. Subsequent analyses were completed in 2008 on the Bingaman-Specter and Lieberman-Warner bills. Mr. de la Chesnaye was a lead author for the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report and served as the U.S. government's lead technical expert on long-term economic and emission scenarios. Mr. de la Chesnaye is co-editor of *Human-Induced Climate Change: An Interdisciplinary Assessment* (2007). He is co-editor of "Multigas Mitigation and Climate Policy" an *Energy Journal Special Issue* (2006). Mr. de la Chesnaye is currently pursuing a Ph.D. in public policy at the University of Maryland. He holds graduate degrees in environmental science from Johns Hopkins University and in economics from American University, and an undergraduate degree in economics from Norwich University, the Military College of Vermont.

Peter C. Evans is general manager of global strategy and planning at GE Energy Infrastructure where he tracks and analyzes political, economic, and regulatory policy trends around the world and the related implications for GE Energy's long-term strategy. Prior to joining GE, he was director, Global Oil, and research director of the Global Energy Forum at Cambridge Energy Research Associates (CERA). He also worked as an independent consultant for a variety of corporate and government clients, including Rio Tinto, American Superconductor Corporation, U.S. Trade Promotion Coordinating Committee, U.S. Department of Energy, the Organization for Economic Cooperation and Development, and the World Bank. Dr. Evans has extensive international energy experience, including two years as a visiting scholar at the Central Research Institute for the Electric Power Industry in Tokyo, Japan. His many articles and policy monographs include *Japan: Bracing for an Uncertain Energy Future* (2006), *Liberalizing Global Trade in Energy Services* (2002), and "International Conflict and Cooperation in Government Export Financing" (2001). He also co-authored CERA's global energy scenario study "Dawn of a New Age: The Energy Future to 2030." Dr. Evans holds a B.A. in government and public policy from Hampshire College, an M.C.P. in economic development and regional planning from the Massachusetts Institute of Technology (MIT), and a Ph.D. in political science from MIT.

Richard J. Goettle IV is a lecturer in the Finance and Insurance Group at the College of Business Administration, Northeastern University. Dr. Goettle holds a B.A. degree in mathematics and computer science from Miami University, a M.B.A. from Northwestern University, and a Ph.D. in economics from the University of Cincinnati. He is the president, co-founder, and principal of Cambridge Planning and Analytics Inc., a developer and marketer of DATADISK Information Services. Dr. Goettle also serves as a senior economist with Dale W. Jorgenson Associates and was with the National Center for Analysis of Energy Systems at Brookhaven National Laboratory. He has written extensively on the general equilibrium consequences of U.S. energy, environmental, and tax policies. Dr. Goettle is a member of the American Economic Association and the Western Economic Association.

Howard Gruenspecht has worked extensively on electricity policy issues, including restructuring and reliability, regulations affecting motor fuels and vehicles, energy-related environmental issues, and economy-wide energy modeling at the U.S. Energy Information Administration (EIA). Before joining EIA, he was a resident scholar at Resources for the Future. From 1993 to 2000, Dr. Gruenspecht served as director of economic, electricity, and natural gas analysis in the Department of Energy's

(DOE's) Office of Policy, having originally come to DOE in 1991 as deputy assistant secretary for economic and environmental policy. His accomplishments as a career senior executive at DOE have been recognized with three Presidential Rank awards. Prior to his service at DOE, Dr. Gruenspecht was senior staff economist at the Council of Economic Advisers (1989-1991), with primary responsibilities in the areas of environment, energy, regulation, and international trade. His other professional experience includes service as a faculty member at the Graduate School of Industrial Administration, Carnegie-Mellon University (1981-1988), economic adviser to the chairman of the U.S. International Trade Commission (1988-1989), and assistant director, economics and business, on the White House Domestic Policy Staff (1978-1979). Dr. Gruenspecht received his B.A. from McGill University in 1975 and his Ph.D. in economics from Yale University in 1982.

Bryan Hubbell is senior advisor for science and policy analysis for the Health and Environmental Impacts Division in the Office of Air and Radiation in the U.S. Environmental Protection Agency. He has written and presented extensively on the health impacts and economic benefits and costs of air quality regulations, serving as the principal benefits analyst for many of EPA's recent regulatory analyses, and led the project team that developed the environmental Benefits Mapping and Analysis Program (BenMAP). His research interests include health impact assessments methods, integrated climate and air quality assessment models, reduced form air quality modeling, selection of optimal controls to maximize net benefits of air quality regulations, and improving valuation of health and environmental changes.

Nathaniel Keohane is director of economic policy and analysis at Environmental Defense Fund (EDF). Dr. Keohane oversees EDF's analytical work on the economics of climate policy, and helps to develop and advocate the organization's policy positions on global warming. His academic research has focused on the design and performance of market-based environmental policies. Dr. Keohane has a Ph.D. in political economy and government (2001) from Harvard University, and a B.A. (1993) from Yale College. From 2001 to 2007, Dr. Keohane was an assistant and then associate professor of economics at the Yale School of Management. He has published articles on environmental economics in academic journals including the *Journal of Public Economics*, the *RAND Journal of Economics*, the *Journal of Environmental Economics and Management* and the *Harvard Environmental Law Review*. Dr. Keohane is also the co-author of *Markets and the Environment* (2007) and co-editor of *Economics of Environmental Law* (forthcoming).

Ray Kopp holds Ph.D. and M.A. degrees in economics and an undergraduate degree in finance. He has been a member of the Resources for the Future (RFF) research staff since 1977 and has held a variety of management positions within the institution. Dr. Kopp's interest in environmental policy began in the late 1970s when he developed techniques to measure the effect of pollution control regulations on the economic efficiency of steam electric power generation. He then led the first examination of the cost of major U.S. environmental regulations in a full, general equilibrium, dynamic context by using an approach that is now widely accepted as state of the art in cost-benefit analysis. During his career Dr. Kopp has specialized in the analysis of environmental and natural resource issues with a focus on federal regulatory activity. He is an expert in techniques of assigning value to environmental and natural resources that do not have market prices, which is fundamental to cost-benefit analysis and the assessment of damages to natural resources. Dr. Kopp's current research interests focus on the design of domestic and international polices to combat climate change.

Tom Kram is program manager for integrated assessment modeling at the Netherlands Environmental Assessment Agency (now PBL: formerly MNP and RIVM). His core responsibilities include the development and application of the IMAGE modeling framework, working with national and international research partnerships. The IMAGE model is developed to address issues arising from human development and related environmental concerns, with focus on mutual relationships and feedbacks between natural and human systems at the global scale. He earned an M.Sc. degree in electrical engineering and operations research from Technical University Delft, specializing in economics of electric power production. Before coming to PBL, he worked at the Energy Research Centre. Besides sectoral and technological assessments, and energy, technology, and climate policy support work, he spent much of his time on running the Energy Technology Systems Analyis Project (ETSAP), developing and applying the MARKAL model. Over the life of IPCC, he has contributed to its work in a variety of functions, including lead author of the 2nd Assessment Report and the Special Report on Emissions Scenarios (SRES). Currently he is member of IPCC-TGICA, a task group set up to support data and scenario information for impact and climate analysis. Current research focuses on the role of land use in as pivot for climate change impacts, adaptation and mitigation (e.g., bio-energy, forestry options) in close conjunction with providing other ecological goods and services for human development (food, water, biodiversity, and so on).

John A. "Skip" Laitner is the director of economic analysis for the American Council for an Energy-Efficient Economy (ACEEE). He previously served almost 10 years as a senior economist for technology policy for the U.S. Environmental Protection Agency (EPA), but chose to leave the federal service in June 2006 to focus his research on developing a more robust analytical characterization of energy efficiency resources for energy and climate policy analyses and within economic policy models. In 1998 Mr. Laitner was awarded the EPA's Gold Medal for his work with a team of other EPA economists to evaluate the impact of different strategies that might assist in the implementation of greenhouse gas emissions reduction policies. In 2003 the U.S. Combined Heat and Power Association gave him an award to acknowledge his contributions to the policy development of that industry. In 2004 his paper "How Far Energy Efficiency?" catalyzed new research into the proper the characterization of efficiency as a long-term resource. Author of more than 200 reports, journal articles, and book chapters, Mr. Laitner has more than 38 years of involvement in the environmental and energy policy arenas. He has been invited to provide technical seminars in diverse places as Australia, Canada, China, France, Germany, Korea, South Africa, and Spain. He served as an adjunct faculty member for the Virginia Polytechnic Institute and State University and the University of Oregon, teaching graduate courses on the economics of Technology. He has a master's degree in Resource Economics from Antioch University in Yellow Springs, Ohio.

Robert Marlay is the deputy director of the U.S. Climate Change Technology Program (CCTP). Dr. Marlay is a career member of the Government's Senior Executive Service and serves concurrently as deputy director of the Office of Climate Change Policy and Technology (CCPT) in the Office of Policy and International Affairs at the U.S. Department of Energy (DOE). He has more than 30 years of federal service and has been with the DOE and its predecessor agencies since 1974. His contributions have focused primarily in the areas of national security, energy policy, science policy, and management of research and development programs. Earlier, Dr. Marlay served as director of DOE's Office of Science and Technology Policy. He has also held leadership positions in the Offices of Science, Energy Efficiency and Renewable Energy, and in the Federal Energy Administration. He holds a B.S.E. degree from Duke University, as well as two masters degrees and a Ph.D. from the Massachusetts Institute of Technology.

W. David Montgomery is vice president and co-leader of CRA International's global energy and environment practice. He is an internationally recognized expert on economic issues associated with climate change policy, and his work on these topics has been published frequently in peer-reviewed journals. He was a principal lead author of the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Working Group III, and has authored a number of peer-reviewed publications on climate policy over the past 20 years. Dr. Montgomery's current research deals with economic impacts of climate policies, design of R&D policy, and how economic and political institutions affect the design and effectiveness of climate policies. He has led a number of strategic assessments for clients in the private sector, advising them on how future climate policies and other environmental regulations could affect their asset value, investment decisions, and strategic direction. He is the author of recent studies on the design of California's policies to limit greenhouse gas emissions and on the economic impacts of U.S. climate legislation. He testified at hearings on climate policy held by the Ways and Means and Foreign Relations committees of the U.S. House of Representatives during the 110th Congress. Prior to joining CRA International, Dr. Montgomery held a number of senior positions in the United States government. He was assistant director of the U.S. Congressional Budget Office and deputy assistant secretary for policy in the U.S. Department of Energy. He taught economics at the California

Institute of Technology and Stanford University, and he was a senior fellow at Resources for the Future. Dr. Montgomery holds a Ph.D. in economics from Harvard University and was a Fulbright Scholar at Cambridge University. He received the Association of Environmental and Resource Economists' 2005 award for a "Publication of Enduring Quality" for his pioneering work on emission trading.

Brian Murray joined the Nicholas Institute at Duke University in 2006 as director for economic analysis. Before that, he was director of the Center for Regulatory Economics and Policy Research at RTI International. He specializes in developing and applying economic models to analyze environmental and natural resource policies, programs, and regulations. He is a widely recognized expert in the integration of economic and biophysical models to assess greenhouse gas mitigation strategies in agriculture, land use change, and forestry. In pollution control, he has examined the economic effects of traditional command-based regulatory strategies and more market-oriented approaches such as emissions fees. Dr. Murray's work has been published extensively in professional journals, edited book volumes, and commissioned reports. He has been invited as a co-author of several national and international assessments of forest resources, especially related to climate change. He received his Ph.D. in resource economics from Duke in 1992.

Nebojša Nakićenović is professor of energy economics at the Vienna University of Technology (TU Wien), acting deputy director of the International Institute for Applied Systems Analysis (IIASA), and director of the Global Energy Assessment (GEA). Dr. Nakićenović holds bachelor's and master's degrees in economics and computer science from Princeton University and the University of Vienna, where he also completed his Ph.D. He also holds an Honoris Causa Ph.D. degree in engineering from the Russian Academy of Sciences.

William D. Nordhaus is Sterling Professor of Economics at Yale University. He has been on the faculty of Yale since 1967 and has been full professor of economics since 1973. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences. He is on the research staff of the Cowles Foundation and of the National Bureau of Economic Research and has been a member and senior advisor of the Brookings Panel on Economic Activity, Washington, D.C., since 1972. Dr. Nordhaus is current or past editor of several scientific journals and has served on the executive committees of the American Economic Association and the Eastern Economic Association. He serves on the Congressional Budget Office Panel of Economic Experts and was the first chair of the Advisory Committee for the Bureau of Economic Analysis. He was the first chair of the American Economic Association Committee on Federal Statistics. In 2004, he was awarded the prize of "Distinguished Fellow" by the American Economic Association. From 1977 to 1979, he was a member of the President's Council of Economic Advisers. From 1986 to 1988, he served as the provost of Yale University. He has served on several committees of the National Research Council, including the Committee on Nuclear and Alternative Energy Systems, the Panel on Policy Implications of Greenhouse Warming, the Committee on National Statistics, the Committee on Data and Research on Illegal Drugs, and the Committee on the Implications for Science and Society of Abrupt Climate Change. His research has focused on economic growth and natural resources, as well as the question of the extent to which resources constrain economic growth. Since the 1970s, he has developed economic approaches to global warming, including the construction of integrated economic and scientific models (the DICE and RICE models) to determine the efficient path for coping with climate change, with the latest vintage, DICE-2007, completed in the spring of 2007. Dr. Nordhaus completed his undergraduate work at Yale University and received his Ph.D. in economics in 1967 from the Massachusetts Institute of Technology.

Tim Profeta came to Duke University in 2005 as founding director of the Nicholas Institute for Environmental Policy Solutions. Prior to this, he served as counsel for the environment to Senator Joseph Lieberman. As Senator Lieberman's counsel, Mr. Profeta was a principal architect of the Lieberman-McCain Climate Stewardship Act of 2003. He also represented Senator Lieberman in legislative negotiations pertaining to environmental and energy issues, as well as coordinating the senator's energy and environmental portfolio during his runs for national office. Mr. Profeta has served as a visiting lecturer at Duke Law School, where he taught a weekly seminar on the evolution of environmental law and the Endangered Species Act. Before joining Senator Lieberman's staff, he was a law clerk for Judge Paul L. Friedman, U.S. District Court for the District of Columbia.

John Reilly is an energy, environmental, and agricultural economist at the Massachusetts Institute of Technology, where his work focuses on understanding the role of human activities as a contributor to global environmental change and the effects of environmental change on society and the economy. A key element of his work is the integration of economic models of the global economy as it represents human activity with models of biophysical systems including the ocean, atmosphere, and terrestrial vegetation. By understanding the complex interactions of human society with our planet, the goal is to aid in the design of policies that can effectively limit the contribution of human activity to environmental change, to facilitate adaptation to unavoidable change, and to understand the consequences of the deployment of large scale energy systems that will be needed to meet growing energy needs.

Martin T. Ross specializes in environmental/energy economics and macroeconomic-simulation modeling at RTI International. While at RTI, Dr. Ross has developed the ADAGE model, a dynamic computable general equilibrium (CGE) model designed to estimate international and U.S. regional impacts of policies on economic variables such as GDP, industrial output, household consumption, and investment. The model is particularly useful for examining how climate-change mitigation policies limiting carbon dioxide (CO_2) emissions from energy consumption and non-CO_2 greenhouse gas (GHG) emissions will affect all sectors of the economy. Current research being conducted for the U.S. EPA, the Pew Center on Global Climate Change, and the Nicholas Institute at Duke University involves using the ADAGE model to estimate U.S. macroeconomic impacts of several emissions reductions policies. Other work at RTI has involved developing a detailed technology model of electricity markets to examine how criteria pollutant and GHG policies affect capacity planning decisions and generation costs. Dr. Ross joined RTI in 2003 after spending several years at Charles River Associates where he developed regional models to look at effects of climate-change mitigation policies and macroeconomic impacts of electric-utility legislation.

Ed Rubin is the Alumni Professor of Environmental Engineering and Science and a professor of engineering and public policy and of mechanical engineering at Carnegie Mellon University. Dr. Rubin's research deals with technical, economic and policy issues related to energy and the environment. One major focus is on design and analysis of environmental control options for electric power systems. Research sponsored by the U.S. Department of Energy has developed the Integrated Environmental Control Model (IECM)—a model widely used for engineering and economic analysis of current and advanced power generation systems and environmental control options. Recent model applications include a comparative assessment of coal combustion, natural gas combined cycle, and integrated coal gasification combined cycle (IGCC) power generation systems with and without CO_2 capture and sequestration as a potential measure to mitigate global climate change. Recent research on technological innovation has examined the influence of government policies to meet environmental goals. Learning curves derived from case studies of environmental technologies and energy conversion processes have been used estimate future costs of carbon sequestration and global impacts of alternative climate policies. Professor Rubin also is actively involved in national and international assessments of technologies and policies related to energy R&D planning, coal utilization, and climate change mitigation.

Robert Shackleton is a principal analyst in the Macroeconomic Analysis Division of the Congressional Budget Office. His principal areas of research include the economics of climate change, the international macroeconomic implications of the global demographic transition, and retirement preparations among baby boomers. He has also published on the quantification of dialect variation, especially as it bears on the origin and diffusion of features of American dialects. He earned his B.A. in economics and political science from Yale College and his M.A. and Ph.D. at the University of Maryland at College Park.

Joel B. Smith, vice president with Stratus Consulting, has been analyzing climate change impacts and adaptation issues for more than 20 years. He was a coordinating lead author for the synthesis chapter on climate change impacts for the Third Assessment Report of the Intergovernmental Panel on Climate Change and was a lead author for the IPCC's Fourth Assessment Report. He has provided technical advice, guidance, and training on assessing climate change impacts and adaptation to people around the world and for clients such as the U.S. Environmental Protection Agency, the U.S. Agency for International Development, the U.S. Country Studies Program, the World Bank, the United Nations, a number of states and municipalities in the United States, the Pew Center on Global Climate Change, the Electric Power Research Institute, the National Commission on Energy Policy, and the Rockefeller Foundation. Mr. Smith worked for the U.S. EPA from 1984 to 1992, where he was the deputy director of Climate Change Division. He is a coeditor of EPA's Report to Congress: *The Potential Effects of Global Climate Change on the United States* (1989); *As Climate Changes: International Impacts and Implications* (1995); and *Adaptation to Climate Change: Assessments and Issues* (1996), *Climate Change, Adaptive Capacity, and Development* (2003), and *The Impact of Climate Change on Regional Systems: A Comprehensive Analysis of California* (2006). He joined Hagler Bailly in 1992 and Stratus Consulting in 1998. He has published more than two dozen articles and chapters on climate change impacts and adaptation in peer-reviewed journals and books. Besides working on climate change issues at EPA, he also was a special assistant to the assistant administrator for the Office of Policy, Planning, and Evaluation. Mr. Smith was a presidential management intern in the Office of the Secretary of Defense from 1982 to 1984. He has also worked in the U.S. Department of Energy and the U.S. Agency for International Development. Mr. Smith received a B.A. (magna cum laude) from Williams College in 1979, and a masters in public policy from the University of Michigan in 1982.

Dimitri Zenghelis recently joined Cisco's long term innovation group as chief economist of the Climate Change practice in the Global Public Sector organization. He has moved from heading the Stern Review Team at the Office of Climate Change, London. Previously, he was a senior economist who has spent a year working with Lord Stern on the Stern Review on Economics of Climate Change, commissioned by the then Chancellor Gordon Brown. He continues to act as an external advisor to the government of the United Kingdom and works closely with Lord Stern at the LSE where he is a senior visiting fellow at the Grantham Institute on Climate Change. He is also an associate fellow at the Royal Institute of International Affairs (Chatham House). Mr. Zenghelis joined HM Treasury in 1999, providing economic analysis and advice for the government of the United Kingdom as head of economic forecasting and head of the European Monetary Union Analysis Branch.